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# Graduate

To Mines Graduate Students:
This catalog is for your use as a source of continuing reference. Please save it.

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Colorado School of Mines,
Golden, CO 80401

Address correspondence:

Office of Graduate Studies
Colorado School of Mines
Golden, CO 80401
Telephone: 303-384-2551
https://www.mines.edu/graduate-studies/contact/

# General Information

## Graduate Catalog

Beginning in Fall 2024, the undergraduate catalog will incorporate course-level learning outcomes. While the learning outcomes presented in this edition of the catalog may be outdated, they will be revised and ensured for accuracy in subsequent updates.

## Graduate Student Profile

Mines graduate students identify and address grand challenges of the twenty-first century using innovative applications of sound scientific and engineering principles. They act as contributors and leaders of multidisciplinary teams to deliver impactful results for the betterment of society.

Mines graduate students are skilled in the acquisition, interpretation, and analysis of data as well as communication of information to diverse audiences. They exemplify ethical behavior including academic and professional integrity, respect for diversity of all types, and recognition of the value of living and working in an interdependent world.

## Institutional Values and Principles

## Graduate Education

Colorado School of Mines has been powering industry, Colorado and the future since 1874. Our STEM-focused education and research produce the talent, knowledge and solutions to serve industry and benefit society – all to create a more prosperous future. It's the mission Mines was founded on 150 years ago and where we continue to excel today. We're a community of innovative leaders and resilient problem-solvers who revel in challenges and work together in order to engineer solutions on Earth and beyond.

Mines is a world-renowned institution that continually enhances its leadership in education and research to serve and advance industry, government agencies and communities around the world. By maximizing its top-ranked academic programs, close industry connections, cutting-edge research and a global alumni network, Mines is the go-to place for distinction and expertise in both established and emerging engineering and scientific fields.

Mines seeks to instill in all graduate students a broad class of developmental and educational attributes that are guided by a set of institutionally vetted educational objectives and student learning outcomes. For doctoral, master's and certificate programs, these are summarized below.

## Doctoral Programs

*Institutional Educational Objectives:*

1. Advance the state of the art of their discipline (integrating existing knowledge and creating new knowledge) by conducting independent research that addresses relevant disciplinary issues and by disseminating their research results to appropriate target audiences.
2. Be scholars and international leaders who exhibit the highest standards of integrity.
3. Advance in their professions and assume leadership positions in industry, government, and academia.

*Institutional Student Outcomes:*

1. Demonstration of exemplary disciplinary expertise.
2. Demonstration of a set of skills and attitudes usually associated with our understanding of what it is to be an academic scholar (e.g., intellectual curiosity, intellectual integrity, intellectual independence, ability to think critically and argue persuasively, ability to direct, conduct, interpret, and disseminate research, a passion for lifelong learning, etc.).
3. Demonstration of a set of professional skills (e.g., oral and written communication, time-management, project planning, teaching, teamwork and team leadership, cross-cultural and diversity awareness, etc.) necessary to succeed in a student's chosen career path.

## Master's Programs

Colorado School of Mines offers a wide variety of master's-level degree programs that include thesis and non-thesis Master of Science programs, Master of Engineering programs and professional master's programs. While the objectives and outcomes provided below document expectations of all master's-level programs, it is expected that, given the diversity of program types, different programs will emphasize some objectives and outcomes more than others.

*Institutional Educational Objectives:*

Master's graduates will

1. Contribute to the advancement of their chosen fields through adopting, applying and evaluating state-of-the-art practices.
2. Be viewed within their organizations as technologically advanced and abreast of the latest scholarship.
3. Exhibit the highest standards of integrity in applying scholarship.
4. Advance in their professions.

*Institutional Student Outcomes:*

Demonstration of

1. Exemplary disciplinary expertise.
2. The ability to conduct and direct research, the ability to assimilate and assess scholarship, and the ability to apply scholarship in new, creative and productive ways.
3. Professional skills (e.g., oral and written communication, time management, project planning, teamwork and team leadership,

cross-cultural and diversity awareness, ethics, etc.) necessary to succeed in a student's chosen career path.

## Certificate Programs

Colorado School of Mines offers a variety of certificate programs. While the objectives and outcomes provided below document expectations of all certificate programs, it is expected that given the diversity of program types, different programs will emphasize some objectives and outcomes more than others.

*Institutional Educational Objectives:*

Recipients will

1. Contribute to the advancement of their chosen fields through adopting, applying and evaluating state-of-the-art practices.
2. Be viewed within their organizations as technologically advanced and abreast of the latest developments in the field.
3. Exhibit the highest standards of integrity in applying their background to problems.
4. Advance in their professions.

*Institutional Student Outcomes:*

1. Demonstration of exemplary disciplinary expertise.

## Research

The creation and dissemination of new knowledge are the primary responsibilities of all members of the university community and fundamental to the educational and societal missions of the institution. Public institutions have an additional responsibility to use that knowledge to contribute to the economic growth and public welfare of the society from which they receive their charter and support. As a public institution of higher education, a fundamental responsibility of Mines is to provide an environment that enables contribution to the public good by encouraging creative research and ensuring the free exchange of ideas, information, and results. To this end, the institution acknowledges the following responsibilities:

- To ensure that these activities are conducted in an environment of minimum influence and bias, it is essential that Mines protects the academic freedom of all members of its community.
- To provide the mechanisms for creation and dissemination of knowledge, the institution recognizes that access to information and information technology (e.g., library, computing, and internet resources) are part of the basic infrastructure support to which every member of the community is entitled.
- To promote the utilization and application of knowledge, it is incumbent upon Mines to define and protect the intellectual-property rights and responsibilities of faculty members, students, and staff as well as the institution.
- To ensure integration of research activities into its basic educational mission, its research policies and practices conform to the state non-competition law requiring all research projects have an educational component through the involvement of students and/or postdoctoral fellows.

## Intellectual Property

The creation and dissemination of knowledge are the primary responsibilities of all members of the university community. As an institution of higher education, a fundamental mission of Mines is to provide an environment that motivates the faculty and promotes the creation, dissemination, and application of knowledge through the timely and free exchange of ideas, information, and research results for the public good. To ensure that these activities are conducted in an environment of minimum influence and bias, so as to benefit society and the people of Colorado, it is essential that Mines protects the academic freedom of all members of its community. It is incumbent upon Mines to help promote the utilization and application of knowledge by defining and protecting the rights and responsibilities of faculty members, students, and the institution, with respect to intellectual property which may be created while an individual is employed as a faculty member or enrolled as a student.

## History of Colorado School of Mines

In 1865, only six years after gold and silver were discovered in the Colorado Territory, the fledgling mining industry was in trouble. The nuggets had been picked out of streams and the rich veins had been worked, and new methods of exploration, mining, and recovery were needed.

Visionaries like W.A.H. Loveland, E.L. Berthoud, Arthur Lakes, George West and Episcopal Bishop George M. Randall proposed a school of mines. In 1874, the Territorial Legislature appropriated $5,000 and commissioned Loveland and a Board of Trustees to found the Territorial School of Mines in or near Golden. Governor Routt signed the bill on February 9, 1874, and when Colorado became a state in 1876, Colorado School of Mines was constitutionally established. The first diploma was awarded in 1883.

As Mines grew, its mission expanded from the rather narrow initial focus on nonfuel minerals to programs in petroleum production and refining as well. New interdisciplinary initiatives focused on advanced manufacturing, underground construction and tunneling, nuclear science, earth science policy, aerospace systems, and data analytics are expanding Mines expertise and educational opportunities. Mines sees its mission as education and research in engineering and applied science with a special focus on the earth science disciplines in the context of responsible stewardship of the earth and its resources.

Mines long has had an international reputation. Students have come from nearly every nation, and alumni can be found in every corner of the globe.

## Location

Golden, Colorado, has always been the home of Mines. Located in the foothills of the Rocky Mountains 20 minutes west of Denver, this community of 15,000 also serves as home to the Coors Brewing Company, the National Renewable Energy Laboratory, and a major U.S. Geological Survey facility that also contains the National Earthquake Information Center. The seat of government for Jefferson County, Golden once served as the territorial capital of Colorado. Skiing is an hour away to the west.

## Administration

By state statute, the school is managed by a seven-member board of trustees appointed by the governor, and the student and faculty bodies elect one nonvoting board member each. The school is supported financially by student tuition and fees and by the State through annual appropriations. These funds are augmented by government and privately sponsored research, private gift support from alumni, corporations, foundations and other friends.

## Colorado School of Mines Non-Discrimination Statement

In compliance with federal law, including the provisions of Titles VI and VII of the Civil Rights Act of 1964, Title IX of the Education Amendment of 1972, Sections 503 and 504 of the Rehabilitation Act of 1973, the Americans with Disabilities Act (ADA) of 1990, the ADA Amendments Act of 2008, Executive Order 11246, the Uniformed Services Employment and Reemployment Rights Act, as amended, the Genetic Information Nondiscrimination Act of 2008, and Board of Trustees Policy 10.6, Colorado School of Mines does not discriminate against individuals on the basis of age, sex, sexual orientation, gender identity, gender expression, race, religion, ethnicity, national origin, disability, military service, or genetic information in its administration of educational policies, programs, or activities, admissions policies, scholarship and loan programs, athletic or other school-administered programs, or employment.

Inquiries, concerns, or complaints should be directed by subject content as follows:

The EO, ADA Coordinator, and Section 504 Coordinator for employment:
Craig Hess, Director of Employee Relations
Human Resources Office
1500 Illinois Street
Golden, Colorado 80401
303-273-3390

The ADA Coordinator and the Section 504 Coordinator for students and academic educational programs:
Marla Draper, Director of Disability Support Services
1225 17th Street
Golden, Colorado 80401
303-273-3297
disabilitysupport@mines.edu

Title IX Complaints and Student Discrimination Complaints:
Carole Goddard, Title IX Coordinator
Golden, Colorado 80401
303-273-3206
titleix@mines.edu (kschmalz@mines.edu)

The ADA Facilities Access Coordinator:
Sam Crispin, Director of Facilities Management
1318 Maple Street
Golden, Colorado 80401
303-273-3330

# The Graduate School

https://www.mines.edu/graduate-studies/

## Unique Programs

Because of its special focus, Colorado School of Mines has unique programs in many fields. For example, Mines is the only institution in the world that offers doctoral programs in all five of the major earth science disciplines: Geology and Geological Engineering, Geophysics, Geochemistry, Mining Engineering, and Petroleum Engineering. It also has one of the few Metallurgical and Materials Engineering programs in the country that still focuses on the complete materials cycle from mineral processing to finished advanced materials.

In addition to the traditional programs defining the institutional focus, Mines is pioneering both undergraduate and graduate interdisciplinary programs. Mines understands that solutions to the complex problems involving global processes and quality of life issues require cooperation among scientists, engineers, economists, and the humanities.

Mines offers interdisciplinary graduate programs in areas such as Additive Manufacturing, Advanced Energy Systems, Data Science, Geochemistry, GIS and GeoInformatics, Humanitarian Engineering and Science, Hydrologic Science and Engineering, Materials Science, Nuclear Science and Engineering, Operations Research with Engineering, Quantitative Biosciences and Engineering, Quantum Engineering, Robotics, Space Resources, and Underground Construction and Tunneling Engineering. These programs make interdisciplinary connections between traditional fields of engineering, physical science and social science, emphasizing a broad exposure to fundamental principles while cross-linking information from traditional disciplines to create the insight needed for breakthroughs in the solution of modern problems. Additional interdisciplinary degree programs may be created by Mines' faculty as need arises.

Lastly, Mines offers a variety of non-thesis professional master's degrees to meet the career needs of working professionals in Mines' focus areas.

## Graduate Degrees Offered

Mines offers graduate certificate, professional master's, Master of Science (MS), Master of Engineering (ME) and Doctor of Philosophy (PhD) degrees in the disciplines listed in the chart.

In addition to master's and PhD degrees, departments and programs can also offer graduate and post-baccalaureate certificates. Graduate and post-baccalaureate certificates are designed to have selective focus, short time to completion, and consist of coursework only.

## Accreditation

Mines is accredited at the graduate level, through the doctoral degree, by the following:

The Higher Learning Commission (HLC) of the North Central Association
230 South LaSalle Street, Suite 7-500
Chicago, Illinois 60604-1413
312-263-0456

| Degree Programs | Prof. | M.S. | M.E. | Ph.D. | Cert. |
|---|---|---|---|---|---|
| Additive Manufacturing | | x | | | X |
| Advanced Energy Systems | | x | | x | |
| Analytical Geochemistry | x | | | | x |
| Antennas & Radar Technology | | | | | x |
| Applied Chemistry | | | | x | |
| Applied Mathematics and Statistics | | x | | x | |
| Applied Physics | | x | | | |
| Business Analytics | | | | | x |
| Carbon Capture, Utilization and Storage | | x | | | x |
| Chemical Engineering | | x | | x | |
| Chemical Engineering Processes in Energy Transitions | | | | | x |
| Chemistry | | x | | | |
| Civil & Environmental Engineering | | x | | x | |

| | | | | | |
|---|---|---|---|---|---|
| Computer Science | x | x | | x | |
| Computer Science Professional | | | | | x |
| CyberSecurity | | | | | x |
| Data Science | | x | | | |
| Data Science - Computer Science | | | | | x |
| Data Science - Foundations | | | | | x |
| Data Science - Petroleum Data Analytics | | | | | x |
| Data Science for Signals and Systems | | | | | x |
| Data Science - Statistical Learning | | | | | x |
| Earth Resources Data Science | | | | | x |
| Earth Resources Science and Engineering | | x | | x | |
| Economic Geology | | | | | x |
| Electrical Engineering | x | x | | x | |
| Electrical Engineering - Information and System Sciences | | | | | x |
| Electrical Engineering - Microwave Engineering | | | | | x |
| Electrical Engineering - Power and Energy Systems | | | | | x |
| Energy Geophysics | | | | | x |
| Engineering & Technology Management | | x | | | |
| Environmental Geochemistry | x | | | | |
| Environmental Engineering Science | | x | | x | |
| Environmental Modeling | | | | | x |
| Exploration Methods | | | | | x |
| Finite Element Analysis Professional | | | | | x |
| Geochemistry | | x | | x | |
| Geological Engineering | | x | x | x | |
| Geology | | x | | x | |
| Geophysical Engineering | | x | | x | |
| Geophysics | | x | | x | |
| GIS & GeoInformatics | | x | | | |
| GIS & Geoinformatics: Geospatial Information Technology | | | | | x |
| GIS & Geoinformatics: GIS for Environmental Studies | | | | | x |
| GIS & Geoinformatics: GIS for Geohazards Evaluation | | | | | x |
| GIS & Geoinformatics: GIS for Natural Resources Assessment | | | | | x |
| Humanitarian Engineering & Science | | x | | | x |
| Hydrology | | x | | x | |
| Materials Science | | x | | x | |
| Mechanical Engineering | | x | | x | |
| Metallurgical & Materials Engineering | | x | x | x | |
| Mineral & Energy Economics | | x | | x | |
| Mineral Exploration | x | | | | |
| Mining Engineering | | x | | x | |
| Mining Industry Management | x | | | | |
| Natural Resources and Energy Policy | | x | | | x |
| Nuclear Science and Engineering | | x | x | x | |
| Operations Research with Engineering | | x | | x | |
| Optics for Engineering | | | | | x |
| Petroleum Engineering | | x | x | x | |
| Physics | | | | x | |
| Product Management | | | | | x |
| Quantitative Biosciences and Engineering | | x | | x | |
| Quantum Engineering | | x | | | x |
| Resource Commodity Analytics | | | | | x |
| RF and Microwave Engineering | | | | | x |
| Robotics | | x | | x | x |
| Smart Grid, Power Electronics & Electrical Power Systems | | x | | | x |
| Space Resources | | x | | x | x |
| STEM Education | | x | | | |
| Tailings Engineering | | | | | x |
| Underground Construction and Tunnel Engineering | | x | | x | x |

# Admission to the Graduate School

## Graduate Admissions

Admission to all graduate programs is competitive and the academic background of each applicant is evaluated according to the individual program requirements.

To earn a post-baccalaureate certificate, a graduate certificate, or a graduate degree, students must have completed an appropriate undergraduate degree program. Colorado School of Mines undergraduate students in the combined degree program may, however, work toward completion of graduate degree requirements prior to completing undergraduate degree requirements. See the Combined Undergraduate/Graduate Degree section below for details about this program.

Refer to Graduate Admissions web page for more information about requirements and deadlines.

## CATEGORIES OF ADMISSION

There are four categories of admission to graduate programs at Colorado School of Mines: regular, provisional, graduate non-degree, and exchange.

### Regular Degree Students

Applicants who meet all the necessary qualifications as determined by the program to which they have applied are admitted as regular graduate students.

## Provisional Degree Students*

Applicants who are not qualified to enter the regular degree program directly may be admitted as provisional degree students for a trial period not longer than 12 months. During this period students must demonstrate their ability to work for an advanced degree as specified by the admitting degree program. After the first semester, the student may request that the department review their progress and make a decision concerning full degree status. With department approval, the credits earned under the provisional status can be applied toward the advanced degree.

*Note: International F1/J1 students are ineligible for provisional acceptance to a graduate degree program.

## Non-Degree Students

Practicing professionals may wish to update their professional knowledge or broaden their areas of competence without committing themselves to a degree program. They can do this by submitting a graduate non-degree application whereby they can enroll in regular courses as non-degree students. Registration in the requested courses is based on availability (after all current students have registered for their courses), completion of the non-degree application, and proof of prerequisites, through the submission of official transcripts.

A person admitted as a non-degree student who subsequently decides to pursue a regular degree program must apply and gain admission to the Graduate School.

- Credits earned as a non-degree graduate student may be used toward the regular graduate degree program if the credits are not prerequisites or deficiencies and the student's graduate committee and department head approve. No more than 3 credits may be used toward a post-baccalaureate or graduate certificate. No more than 9 credits may be used toward a master's or doctoral degree. Graduate non-degree credits count toward the student's graduate cumulative grade-point average (GPA) and could impact a student's academic standing as a degree-seeking graduate student.
- Graduate credits earned as a non-degree undergraduate student may be transferred into the regular graduate degree program. If the credits do not exceed the transfer limits, the transfer credits must not have been used as credit toward a bachelor's degree (students will be required to obtain proof from the bachelor's degree institution), the transfer credits are not prerequisites or deficiency credits and the student's graduate committee and department head approve. Graduate credits taken while an undergraduate non-degree-seeking student count toward the student's undergraduate GPA.

Refer to the Graduate Admissions Requirements webpage for more information about the non-degree application process and deadlines.

## Exchange Students

Graduate-level students living outside the U.S. may wish to take courses at Colorado School of Mines as exchange students. They may enroll in regular courses as exchange students.

A person admitted as an exchange student who subsequently decides to pursue a regular degree program must apply and gain admission to a graduate program.

- All graduate-level credits earned as a graduate foreign exchange student may be used toward the regular graduate degree if the credits are not prerequisites or deficiencies and the student's graduate committee and department head approve. Graduate exchange credits count toward the student's cumulative GPA and could impact academic standing as a degree-seeking student.
- Graduate credits earned as an exchange undergraduate student may be transferred into the regular graduate degree program. If the credits do not exceed the transfer limits, the transfer credits were not used toward a bachelor's degree (students will be required to obtain proof from the bachelor's degree institution), transfer credits are not prerequisites or deficiency credits and the student's graduate committee and department head approve.

Refer to the Office of Global Education Incoming Exchange Students webpage for more information.

## Mines Online Students

Mines offers online graduate degree programs (certificate, master's or PhD) with courses running on an eight-week semester. Admission dates for online programs are posted and may change over time, so check the dates for the program(s) you are interested in applying. You can begin course work as a non-degree-seeking student before being accepted into the program, based on the availability of entry courses. Refer to the Non-Degree Student section under Admission to the Graduate School of this catalog for information on how many credits can be earned prior to admission to a degree program. (p. 5)

# Combined Undergraduate/Graduate Programs

Several degree programs offer Mines undergraduate students the opportunity to begin work on a Graduate Degree while completing the requirements of their Bachelor's Degree. These programs can give students a head start on graduate education. An overview of these combined programs and a description of the admission process and requirements are found in the Graduate Degrees and Requirements section of this catalog.

Admission into a Combined Undergraduate/Graduate degree program is available only to current Mines undergraduate students. Mines alumni are not eligible for Combined degree program enrollment.

Combined students whose graduate degree programs allow double-counting of credits, may only double count if the student has uninterrupted registration from the undergraduate degree to the graduate degree and the student is concurrently enrolled in both the undergraduate and graduate programs for at least one semester (fall or spring). If a student takes a semester or more off between degrees (summer excluded), the student is no longer eligible to double count credits.

Refer to the Combined Program webpage for more information about combined program options, timelines and requirements.

# ADMISSION PROCEDURES

Both U.S. residents and international students must apply electronically for admission. Visit the graduate admissions website for more information about admissions procedures.

To apply follow the procedure outlined below.

**Application**
Go to the online application at https://www.mines.edu/graduate-admissions/apply/ to apply. Since application deadlines vary by program, please refer to our application deadlines webpage for more information.

**Admissions Requirements**

Transcripts, GRE scores, letters of recommendation and other supporting application documents will vary. Please refer to the Graduate Admissions Requirements webpage for more information and details.

**English Language Requirements**
Applicants who are not U.S. citizens or permanent residents and whose native language is not English must prove English proficiency as part of the application process except when applying for a university-approved online program and will be studying outside of the U.S. Applications that do not have valid proof of English proficiency are considered incomplete and will not be released to the department for review. Please refer to the Graduate Admissions Requirement webpage for more information.

## VETERANS

Thank you for your service to our nation. Colorado School of Mines is approved by the Colorado State Approving Agency for Veteran Benefits under chapters 30, 31, 32, 33, 35, 1606, and 1607. Undergraduate students must register for and maintain 12 credits and graduate students must register for and maintain 9 credits of graduate work in any semester to be certified as full-time students for full-time benefits. Any hours taken under the full-time category will decrease the benefits to ¾ time, ½ time, or tuition payment only.

All changes in hours, program, addresses, marital status, or dependents are to be reported to the Veterans Certifying Officer as soon as possible so that overpayment or underpayment may be avoided. Veterans must see the Veterans Certifying Officer each semester to be certified for any benefits for which they may be eligible. In order for veterans to continue to receive benefits, they must make satisfactory progress as defined by Colorado School of Mines.

An honorably or generally discharged military veteran providing a copy of their DD214 is awarded two credits to meet the physical education undergraduate degree requirement at Mines. Additionally, veterans may request substitution of a technical elective for the institution's core EPICS course requirement in all undergraduate degree programs.

Learn more about veteran services and benefits.

## Health Requirements

When students first enroll at Mines, they must complete the student health record form which is sent to them when they are accepted for enrollment.
Refer to the Health Center website for current information on health requirements.

## Statement of Application Fraud

It is your responsibility to ensure that your application information and all supporting documentation are truthful, complete and correct.

Colorado School of Mines reserves the right to verify any information provided as part of your application for admission. It is an act of serious academic misconduct to provide any false or misleading information (either by omission or commission).

If it is proven, or if the University has reasonable grounds to conclude that any information in your application, or in any of the material submitted in support of your application is determined to be false or misleading, or written by a third party, your application may be invalidated. This could result in immediate rejection of your application, or the revocation of an offer of admission, or the termination of your registration at Colorado School of Mines.

## Admissions Decisions

Mines is committed to facilitating a safe environment conducive to academic learning and to compliance with the new legal limitations on inquiries about an applicant's criminal and disciplinary history pursuant to Colorado Senate Bill 19-170 (the Ensuring Access to Higher Education Act), as codified in C.R.S. § 23-5-106.5. Mines will inquire only about the following conduct on the application for student admission:

- An applicant's prior convictions for stalking, sexual assault or domestic violence.
- An applicant's prior convictions, within five years before submitting the application, for assault, kidnapping, voluntary manslaughter or murder.
- An applicant's prior disciplinary history at another academic institution for stalking, sexual assault or domestic violence.
- Any criminal charges pending against the applicant.
- An applicant's education records related to academic performance.

**Notice to Applicants**
In compliance with C.R.S. § 23-5-106.5(2)(b), Mines will notify applicants on the application that they are not required to disclose any information contained in sealed records and have the right to appeal, pursuant to the below procedures, a denial decision made based on any information required to be disclosed. After admission, Mines will inquire into an admitted applicant's conduct history when obtaining information pertaining to participation in campus life.

**Obligation to Update Responses**
Applicants have an obligation to report any updates or changes to their criminal and disciplinary response if they are arrested and charged with any crime after completing their application for admission. Applicants are required to disclose any and all such information in writing to the executive director of Admissions at Mines or, once enrolled, to the dean of students. Failure to report changes that should have been disclosed may result in an allegation of a violation of the Mines Code of Conduct.

**Right to Appeal**
All admissions decisions are final, with one exception. If your admission to Mines is denied based on the information you provided on your application regarding criminal history, pending criminal charges or disciplinary history at another academic institution, you have the right to an appeal.

Appeals must be in writing and should be submitted to the associate provost for Enrollment Management at admissions@mines.edu within 14 days of receipt of the admission decision. Appeals should include all relevant information you would like the associate provost to consider. You will be notified of the outcome of your appeal within 14 days of receipt.

An offer of admission to Mines may be rescinded for, but is not limited to, the following reasons:

- An admitted student is found to have presented misleading or fraudulent information during the application process.

- An admitted student fails to uphold the standards of conduct outlined in Mines Code of Conduct.
- An admitted student has accepted admission both to the Colorado School of Mines and to another graduate program for the same period of enrollment. (Applies only to graduate students.)

Please refer to the Graduate Admissions website for more information.

# Student Life at Mines

Student Life offers a variety of programs, opportunities, and supports for Mines graduate students. To learn more about available services, please visit departmental websites linked from the Division of Student Life website.

# Registration and Tuition Classification

## General Registration Requirements

The normal full-time credit load for graduate students is 9 credits per semester.

Full-time graduate students may register for an overload of up to 6 credits (up to 15 credits total) per semester at no increase in tuition. Subject to written approval by their advisor and department head or program director, students may register for more than 15 credits per semester by paying additional tuition at the regular per credit rate for all credits over 15. The maximum number of credits for which a student can register during the summer is 12.

Students in any of the following categories must register as full-time students.

- International on-campus students subject to immigration requirements. This applies to international students holding J-1 and F-1 visas.
- Students receiving financial assistance in the form of graduate teaching assistantships, research assistantships, fellowships, or hourly contracts.
- Students enrolled in academic programs that require full-time registration. Refer to the degree program sections of this catalog to see if this applies to a particular program.

Special cases to the full-time registration requirement for students listed above fall under Full Time Status-Required Course load and include first-year international students who must receive special instruction to improve their language skills, and thesis-based students who have completed their credit requirements, have completed all required paperwork, are eligible for reduced registration, and are working full time on their thesis (see section on reduced registration). To remain active in their degree program, all graduate students must register continuously each fall and spring semester. If not required to register full time, students may register as a part-time student for any number of credits (1 credit minimum). Students who need to take a semester off must submit paperwork for a Leave of Absence by the appropriate deadline as described below, or the degree program will be terminated.

Summer registration is not required to maintain active status in a graduate program. However, students must register if they are working on their degree requirements and utilizing Mines facilities during the summer. Students registered during the summer are assessed regular tuition and fees.

New graduate students are expected to register for and pay for credits in the term in which they are admitted, including summer admittance.

Graduate students who register for credits in any term are responsible for payment for those credits. Payment information can be found here: https://www.mines.edu/bursar/tuition/.

Graduate students who wish to be dropped from all credits in a term must either submit the Leave of Absence paperwork or the Withdrawal from Graduate School paperwork by the add/drop date of that term. Students who submit either form after the add/drop date may be withdrawn from credits, but will still owe tuition and fees.

Students who wish to be dropped or withdraw from all credits, but do not submit either the Leave of Absence form or the Withdrawal form, will be responsible for paying tuition and fees.

## Research Registration

In addition to completing the required coursework and defending a thesis, students in thesis-based degree programs must complete a research experience under the direct supervision of their faculty advisor(s). Masters students must complete a minimum* of 6 research credits, and doctoral students must complete a minimum* of 24 research credits at Mines. While completing their research, students register for research credit under courses numbered 707. Faculty advisors assign grades indicating satisfactory or unsatisfactory progress based on their evaluation of the student's work.

For students registered for research during the summer semester and working on campus, regular tuition and fees are due for summer semester research credits. Students may not transfer research credits from other institutions, so students working on research abroad must either register for research credits at Mines or submit the Leave of Absence paperwork. Those who take a Leave of Absence may not use any Mines campus resources, including, but not limited to consultations with advisors, committee members and other Mines students during the term of leave.

* Departmental requirements may require students to complete more than the institutional minimum number of research credits.

## Eligibility for Reduced Registration

Students enrolled in thesis-based degree programs who have completed a minimum number of courses and research credits in their degree programs are eligible to continue to pursue their graduate program as full-time students at a reduced registration level. In order to be considered for this reduced, full-time registration category, students must satisfy the following requirements:

1. For MS students,
   a. Completion of 30 credits of eligible course, research, and transfer credits combined (36 if master's degree requires 36 credits), and
   b. Paid for 24 credits (27 if master's degree requires 36 credits).
      i. 1-9 credits per semester count as paid credits; 10-15 credits do not count as paid credits.
2. For PhD students,
   a. Completion of 72 credits of eligible course, research, and transfer credits combined, and

b. Paid for 54 credits.
    i. 1-9 credits per semester count as paid credits; 10-15 credits do not count as paid credits.
3. For all students, an approved thesis committee form and Degree Audit form must be submitted the semester prior to the one for which a student wishes to be in reduced registration status*.
4. PhD students must submit an approved Admission to Candidacy form by the first day of classes in the semester for which the student wishes to be in reduced registration status*.

* See OGS Graduation Deadlines webpage for specific deadlines. Students who are eligible for reduced registration are considered full time if they register for 4 credits of research under course number 707.

## Full-time Status – Required Course Load

To be deemed full-time during the fall and spring semesters, students must register for at least 9 credits.

Alternatively, as described above, if a thesis-based student has completed their required coursework and research credits, has completed all required forms, and has received confirmation from the Office of Graduate Studies that they are eligible for reduced registration, the student will be deemed full-time if they are registered for at least 4 credits of research credit.

Student enrollment is not required during the summer for continuing Mines students, unless it is a condition of holding certain fellowships or an appointment as a research or teaching assistant. To be deemed full-time during the summer, students must register for at least 3 credits.

Note: The above academic definition of full-time for fall, spring, and summer applies to International Students (F and J) for status maintenance purposes.

The definition of full-time for the purpose of qualifying for federal financial aid is 9 credits in fall, spring or summer.

## Transfer Credits

With prior approval, graduate students may use transfer coursework credits toward a master's or PhD degree, but not toward a graduate certificate. All transfer credits must be listed on the Degree Audit form and have the appropriate signatures of approval.

- Masters non-thesis and professional masters students must receive approval from the advisor, co-advisor (if applicable), minor representative (if applicable), and department head/program director.
- Masters thesis and PhD students must receive approval from the advisor, co-advisor (if applicable), all committee members, minor representative (if applicable), and the department head/program director.

Transfer credit limitations apply to all major and minor degrees. Transfer credits from other universities must be for coursework (research credits cannot be transferred except in cases when a full thesis master's program is applied toward a PhD); must be graduate level with a grade of C or better; cannot have been used toward an undergraduate degree and cannot be for prerequisite or deficiency credits. Credits without a letter grade (Pass/Fail, Satisfactory/Unsatisfactory, etc.) will not be accepted as transfer credit.

Grades for transfer credits will not be transferred and therefore will not impact a student's graduate GPA

The Admissions Office must have official transcripts on file prior to transferring credit from another university.

Due to time constraints of receiving transcripts and grades, students taking or wishing to apply transfer credits in their last semester may not be able to graduate in that semester. Students studying abroad are encouraged to not do so during their last semester.

Major degree transfer credit limitations:

- 30-credit master’s non-thesis degree programs are limited to no more than 9 transfer credits.
- 36-credit master’s non-thesis degree programs are limited to no more than 15 transfer credits.
- 30-38-credit master’s thesis degree programs are limited to no more than 9 transfer credits.
- PhD students transferring a thesis-based master’s degree from another university* may transfer up to 36 credits.
- PhD students transferring individual coursework, or any graduate-level degree other than a thesis-based master’s degree from another university,* may transfer up to 24 credits.
    - *Any credits taken at Mines and listed on a Mines graduate-level transcript are not transfer credits.
    - *PhD students may, with committee and department head/ program director approval, use all credits from a Mines master’s degree toward a PhD, as long as the credits were not used toward two Mines master’s degrees.

Minor degree transfer credit limitations:

- Less than half of the minor credit requirement may be transfer credits.
    - Masters students may transfer no more than 4 credits toward a minor.
    - PhD students may transfer no more than 5.5 credits towards a minor.

Transfer credit conversion:

Colorado School of Mines uses semester credits. Any transfer credits taken at a university that does not use semester credits will have the credits converted. U.S. Quarter credits are equivalent to # semester credits. European Credit Transfer and Accumulation System (ECTS) credits are equivalent to ½ semester credits. Other credits will be assessed on an individual basis.

## Dropping and Adding Courses

Students may add or drop some, but not all credits, through web registration without paying a fee during the add/drop period listed on the Academic Calendar. Graduate students who wish to drop all credits during the fall or spring term must submit either the Leave of Absence or Withdrawal from Graduate School paperwork by the add/drop deadline.

## Withdrawing from Courses

After the add/drop date, students may withdraw through web registration from some credits, but not all, for any reason. In this situation students receive a grade of “W” for the withdrawn credits through the last day to withdraw noted on the Academic Calendar. Students who wish to withdraw from all credits must submit a Withdrawal from Graduate School form if they intend to leave Mines. If a student wishes to remain

in a degree program after withdrawing from all credits, they must either register for the immediately subsequent semester to avoid being withdrawn involuntarily from Graduate School, or submit Leave of Absence paperwork (if required by program; see catalog section on Leave of Absence) by the add/drop date in the subsequent term.

After the last day to withdraw on the Academic Calendar, no withdrawals are permitted, except in case of complete withdrawal from graduate school. If extenuating circumstances apply, contact the Office of Graduate Studies.

Any student on approved Leave of Absence must submit a Return from Leave form. The student will be reinstated to active status upon approval of their return by their advisor and their department head or program director.

Students who have already used two semesters of Leave of Absence will need to submit the Withdrawal from Graduate School form if they are not able to return after the second semester of leave. Students who withdraw from graduate school will need to reapply for admission online and be re-accepted.

The financial impact of a withdrawal is covered in the section on "Payments and Refunds."

## Auditing Courses

As part of the maximum of 15 credits of graduate work, students may enroll for no credit (NC) in a course with the permission of the instructor. Tuition charges are the same for no credit as for credit enrollment.

Students must enroll for no credit before, the last day of registration. The form to enroll for a course for no credit is available from the Registrar's Office. NC designation is awarded only if all conditions stipulated by the course instructors are met by the student by the end of the semester.

Mines requires that all U.S. students who are being supported by the institution register full time, and federal financial aid regulations prohibit Mines from counting NC registration in determining financial aid eligibility. In addition, the Immigration and Naturalization Service (INS) requires that international students register full time, and Mines is discouraged from counting NC registration toward that requirement. Furthermore, there are no consistent standards for expectations of students who register for NC in a course. Therefore, in order to treat all Mines students consistently, NC registration will not count toward the minimum number of credits for which students are required to register. This includes the minimum continuous registration requirement of part-time students and the 9-credit requirement for students who must register full time.

The reduced registration policy is based on the principle that the minimum degree requirement (30 or 36 credits for a master's thesis program or 72 credits for a PhD) includes only the credits applied toward that degree. Deficiency and extra courses are above and beyond that minimum. NC courses fall into the latter category and may not be applied toward the degree. Therefore, NC registration does not count toward the number of credits required for a student to be eligible for reduced registration status.

NC registration may involve additional effort on the part of faculty to give and/or grade assignments or exams, so it is the institution's policy to charge tuition for NC courses. Therefore, NC registration will count toward the maximum number of credits for which a graduate student may be allowed to register. This includes a tuition surcharge for credits taken over 15.

## Off-Campus Study

A student must enroll in an official Mines course for any period of off-campus, course-related study, whether U.S. or abroad, including faculty-led short courses, study abroad, or any off-campus trip sponsored by Mines or led by a Mines faculty member. The registration must occur in the same term that the off-campus study takes place. In addition, the student must complete the necessary release, waiver, emergency contact forms, transfer credit pre-approvals, and FERPA release, as well as providing adequate proof of current health insurance prior to departure. For additional information concerning study abroad requirements, contact the Office of Global Education at https://www.mines.edu/global/study-abroad-student-exchange/. For other information, contact the Registrar's Office.

Students conducting research off campus must either register for research credits at Mines or submit the Leave of Absence paperwork. Students on leave may not use any campus resources, including work with advisor, committee members and any Mines students.

Students conducting research abroad must comply with the research off-campus rules above and need to register with the Study Abroad Office. Students may not transfer research credits from another university. All graduate students must register for credits at Colorado School of Mines for at least one semester. A semester of study abroad does not count toward this requirement.

Students studying abroad who are using study abroad transfer credits toward a degree program must have official transcripts on file with the Registrar's Office prior to graduation. Since overseas transcripts often take longer to arrive than U.S. transcripts, students who are studying abroad during their last semester may not be able to graduate in that same semester.

Online students please visit Mines Online for additional information on services and support.

## Numbering of Courses

Course numbering is based on the content of material presented in courses:

| Material | Level | Division |
|---|---|---|
| 100-199 | Freshman Level | Lower Division |
| 200-299 | Sophomore Level | Lower Division |
| 300-399 | Junior Level | Upper Division |
| 400-499 | Senior Level | Upper Division |
| 500-599 | Graduate Level | |
| 600-699 | Advanced Graduate Level | |
| Over 700 | Graduate Research or Thesis Level | |

# Graduation Requirements

## Graduation REGISTRATION and Checkout Requirements

To graduate, students must be registered during the term in which they complete their program.

An exception to this registration policy allows students to complete an early checkout in the spring semester if all requirements have been successfully met by a particular deadline. For additional information, refer to https://www.mines.edu/graduate-studies/graduation-deadlines/.

All graduating students must officially check out of their degree program prior to graduation. Notification of the checkout steps will be sent by the Graduate Office after a student has applied to graduate. Checkout requirements must be completed by the established deadlines for each graduation term.

For detailed information on Graduation, please see the Graduation tab under Academic Regulations.

# Leave of Absence and Parental Leave

## Leave of Absence

Leaves of absence are granted when it is temporarily impossible for students to continue to work toward a degree. Leave of absence requests are required for students in thesis-based programs. Requests for the current semester must be received by the Office of Graduate Studies (OGS) prior to the add/drop date. Leave forms submitted after this date may be considered in extenuating circumstances, but students may only be withdrawn from credits, not dropped. Leave of absence requests for prior semesters will not be considered.

For students in coursework-based Master's or Certificate programs, a formal Leave of Absence request may not be required, depending on the circumstances.  Refer to the Office of Graduate Studies website for additional information regarding periods of non-registration without a Leave of Absence in coursework-based programs.

Any request for a leave of absence must have the prior approval of the student's faculty advisor and department/program, the Office of International Students and Scholars (international students only), and Financial Aid. To request a leave of absence, students must submit the Leave of Absence form to the Graduate office, along with the following information:

1. the reasons why the student must interrupt their studies and,
2. a plan (including a timeline and deadlines) for resuming and completing the work toward the degree in a timely fashion.

Students on leave remain in active standing even though they are not registered for any course or research credits. While on leave, however, students will not have access to Mines resources. This includes, but is not limited to, office space, computational facilities, library, faculty and other Mines students. Students who will be using campus resources in any manner will not be allowed to take a Leave of Absence and will be required to register for at least one credit.

Students are limited to two (not necessarily consecutive) regular semesters of approved leave while in a graduate degree program at Mines. Beyond these two semesters, students needing to suspend their degree programs further are required to formally withdraw from the degree program by submitting the Withdrawal from Graduate School paperwork.

Students on a Leave of Absence must submit the Return from Leave paperwork prior to the start of the subsequent semester if they wish to continue in the degree program. Students on leave who do not submit the Return from Leave paperwork will have the degree program terminated and will need to reapply for admission.

Students who withdraw from graduate school or have their degree program terminated as above will need to reapply, and be readmitted, into the degree program before continuing in the degree program. As with all degree program applications, applications from candidates in these situations are reviewed by the program and considered for readmission at the sole discretion of the program.

Students in thesis-based programs who fail to register and who are not on approved leaves of absence will have their degree programs terminated. Students who wish to return to graduate school after an unauthorized period of absence must apply for readmission.

## Parental Leave

Graduate students in thesis-based degree programs, who have full-time student status and receive TA/RA support at 0.5 FTE level, may be eligible to request up to eight weeks of parental leave. The Parental Leave Policy is designed to assist students who are primary child-care providers immediately following the birth or adoption of a child. The policy is designed to make it possible for students to maintain full-time status in research-based degree programs while taking a leave from that program to care for their new child, and facilitate planning for continuance of their degree program.

Nothing in the Parental Leave policy can, or is intended to, replace communication and cooperation between the student and their advisor, and the good-faith efforts of both to accommodate the birth or adoption of a child within the confines and expectations of participating in a research-active graduate degree program. It is the intent of this Policy to reinforce the importance of this cooperation, and to provide a framework of support and guidance.

### Eligibility

In order to be eligible for Parental Leave, a graduate student must:

- be the primary childcare provider.
- have been a full-time graduate student in their degree program during at least the two prior consecutive semesters.
- be enrolled in a thesis-based degree program (i.e., doctoral or thesis-based master's).
- be in good academic standing as defined in the Unsatisfactory Academic Performance section of this catalog.
- notify advisor of intent to apply for Parental Leave at least four months prior to the anticipated due date or adoption date.
- complete, and have approved, the Request for Parental Leave Form that includes an academic program plan for program continuance at least two months prior to the expected leave date.

### Exceptions and Limitations

This policy has been explicitly constructed with the following limitations:

- Part-time and non-thesis students are not eligible for Parental Leave. These students may, however, apply for a Leave of Absence through the regular procedure defined above.
- If both parents are Mines graduate students who would otherwise qualify for leave under this policy, each is entitled to a Parental Leave period immediately following the birth or adoption of a child during which either one is the primary care provider, but the leaves may not be taken simultaneously.
- Leaves extending beyond eight weeks are not covered by this Policy. The regular Leave of Absence policy defined in the Graduate Catalog applies to these cases.

## Benefits

Under this policy students will receive the following benefits and protections:

- Continuance of assistantship support during the semester in which the leave is taken – only if the student is funded through a TA or RA Contract, as described below.
- Maintenance of full-time status in degree program while on Parental Leave.
- Documentation of an academic plan that specifies both how a student will continue work toward their degree prior to the leave period and how a student will reintegrate into a degree program after returning from leave.

## Planning and Approval

It is the student's responsibility to initiate discussions with their advisor(s) at least four months prior to the anticipated birth or adoption. This notice provides the lead time necessary to rearrange teaching duties (for those students supported by teaching assistantships), to adjust laboratory and research responsibilities and schedules, to identify and develop plans for addressing any new health and safety issues, and to develop an academic program plan that promotes seamless reintegration back into a degree program.

While faculty will make every reasonable effort to meet the needs of students requesting Parental Leave, students must recognize that faculty are ultimately responsible for ensuring the rigor of academic degree programs and may have a direct requirement to meet specific milestones defined in externally funded research contracts. Within this context, faculty may need to reassess and reassign specific work assignments, modify laboratory schedules, etc. Without good communication, such efforts may lead to significant misunderstandings between faculty and students. As such, there must be good-faith and open communication by each party to meet the needs and expectations of each during this potentially stressful period.

The results of these discussions are to be formalized into an academic program plan that is agreed to by both the student and the advisor(s). This plan, to be accepted, must also receive approval by the appropriate department head or program director and the graduate dean. Approval of the dean should be sought by submitting to the Office of Graduate Studies a formal Parental Leave request, with all necessary signatures and the academic program plan developed by the advisor(s) and student, approved by the department head or program director.

These materials should be delivered to the Office of Graduate Studies no less than two months prior to the anticipated date of leave.

If a student and faculty member cannot reach agreement on a program plan, they should consult with the appropriate department head or program director to help mediate and resolve the outstanding issues. As appropriate, the department head or program director may request that the graduate dean and the Office of Institutional Equity provide additional assistance in finalizing the program plan.

## Graduate Students with Appointments as Graduate Research and Teaching Assistants

A graduate student who is eligible for Parental Leave and has a continuing appointment as a research or teaching assistant is eligible for continued stipend and tuition support during the semester(s) in which the leave is taken. For consideration of this support, however, the timing of a leave with continued stipend and tuition support must be consistent with the academic unit's prior funding commitment to the student. No financial support will be provided during leave in a semester in which the student would have otherwise not been funded.

*Tuition and Fee Reimbursement:* If the assistantship, either teaching or research, would have normally paid a student's tuition and mandatory fees, it will continue to do so for the semester(s) in which the Leave is taken. Costs for tuition will be shared proportionally between the normal source of funding for the research or teaching assistantship and the Office of Graduate Studies.

*Stipend Support:* Stipends associated with the assistantship will be provided at their full rate for that portion of the semester(s) during which the student is not on Parental Leave.

No stipend support need be provided during the time period over which the Parental Leave is taken. The student may, however, choose to have the stipend he or she would receive during the semester(s) in which the leave is taken delivered in equal increments over the entire semester(s).

While on leave, students may elect to continue to work in some modified capacity, and faculty, departments and programs may elect to provide additional stipend support in recognition of these efforts. Students, however, are under no obligation to do so, and if they choose to not work during their leave period, this will not be held against them when they return from leave. Upon return, students on research assistantships are expected to continue their normal research activities as defined in their academic program plans. Students on teaching assistantships will be directed by the department or program as to specific activities in which they will engage upon return from parental leave.

## Registration

Students on parental leave should register at the full-time level for research credit hours under the direction of their thesis advisor. The advisor will evaluate student progress toward degree for the semester in which parental leave is taken only on those activities undertaken by the student while he or she is not on leave.

# In-State Tuition Classification Status

## In-State Tuition Classification Status

### General Information

The State of Colorado partially subsidizes the cost of tuition for all students whose domicile or permanent legal residence is in Colorado. Each Mines student is classified as either an “in-state resident” or a “non-resident” at the time of matriculation. These classifications, which are governed by Colorado law, are based upon information furnished by each

student on their application for admission to Mines. A student who willfully furnishes incorrect information to Mines to evade payment of non-resident tuition shall be subject to serious disciplinary action.

It is in the interest of each graduate student who is a U.S. citizen and who is supported on an assistantship or fellowship to become a legal resident of Colorado at the earliest opportunity. Typically, students on an assistantship contract that covers tuition and fees will have the non-resident portion of the tuition paid by Mines during their first year of study only. U.S. citizens are expected to obtain Colorado residency status by the end of the first year of study. Obtaining residency status is not automatic; students must petition through the Registrar's Office. More information on petitioning for residency status as a graduate student can be found here: https://www.mines.edu/registrar/residency-graduate-presentation/. After the first year of study, these students who do not obtain residency status may be responsible for paying the difference between resident and non-resident tuition. International students on an assistantship contract that covers tuition and fees will have the non-resident portion of the tuition paid by Mines beyond the first year.

### Requirements for Establishing Residency as a Graduate Student

The specific requirements for establishing residency for tuition classification purposes are prescribed by state law (Colorado Revised Statutes, Title 23, Article 7). Because residency status is governed solely by Colorado law, the fact that a student might not qualify for in-state status in any other state does not guarantee in-state status in Colorado. The Tuition Classification statute places the burden of proof on the student to provide clear and convincing evidence of eligibility for residency. The final decision regarding tuition status rests with the Residency Appeals Committee of Colorado School of Mines. A student who willfully gives wrong information to evade payment of non-resident tuition shall be subject to serious disciplinary action.

There are two components to determining residency eligibility for graduate students:

- **Domicile** is a person’s true, and permanent home and place of habitation and must be established at least 12 consecutive months prior to the first day of classes.
- **Intent** is the legal ties a person has established to make Colorado their permanent home and must be established concurrently while establishing domicile. This means a student must sever ties from their former state and establish these ties in Colorado. This would include: license, voter registration, vehicle registration, and filing state taxes like any other resident of the state.

More information on how to qualify and petition for resident status, as well as deadlines, can be found on the residency webpage.

### Tuition Classification for WICHE/WRGP Program Participants

WICHE, the Western Interstate Commission for Higher Education, promotes the sharing of graduate-level higher education resources among the participating western states through the Western Regional Graduate Program (WRGP). Under this program, residents of Alaska, Arizona, California, Hawaii, Idaho, Montana, Nevada, New Mexico, North Dakota, Oregon, South Dakota, Utah, Washington, and Wyoming, as well as Commonwealth of the Northern Mariana Islands, Federal States of Micronesia, Guam, American Samoa, Republic of Palau, and Republic of the Marshall Islands, who are enrolled in qualifying graduate programs may be eligible for a discounted tuition classification. Contact Graduate Admissions for more information about WRGP.

Current qualifying programs can be found on the Mines WRGP webpage.

WRGP is considered a public benefit from a student's home state. Therefore, students participating in the program may not petition for residency in Colorado. A student may only claim domicile in one state. A student would need to surrender the WRGP benefit, then fulfill the requirements prescribed by Colorado State law on Tuition Classification for no less than 12 consecutive months before being eligible to be classified as a Colorado resident.

# Academic Regulations

## Graduate School Catalog

It is the responsibility of the graduate student to become informed and to observe all regulations and procedures required by the program the student is pursuing. Ignorance of a rule does not constitute a basis for waiving that rule. The current Graduate Catalog gives the academic requirements the student must meet to graduate. However, with department or program consent, a student can change to the requirements in a later catalog published while the student is enrolled in graduate school. Changes to administrative policies and procedures become effective for all students as soon as the campus community is notified of the changes.

The Graduate Catalog is available to students in both print and electronic forms. Print catalogs are updated annually. Electronic versions of the Graduate Catalog may be updated more frequently to reflect changes approved by the campus community. As such, students are encouraged to refer to the most recently available electronic version of the Graduate Catalog. This version is available at the Mines website. The electronic version of the Graduate Catalog is considered the official version of this document. In case of disagreement between the electronic and print versions, the electronic version takes precedence.

## Curriculum Changes

The Mines Board of Trustees reserves the right to change any course of study or any part of the curriculum to respond to educational and scientific developments. No statement in this catalog or in the registration of any student shall be considered as a contract between Colorado School of Mines and the student.

## Making up Undergraduate Deficiencies

If the department or program decides that new students do not have the necessary background to complete an advanced degree, they will be required to enroll in courses for which they will receive no credit toward their graduate degree, or complete supervised readings, or both. Students are notified of their apparent deficiency areas in their acceptance letter from the Graduate School or in their first interview with their department advisor. Departments will provide the list of deficiencies to the students no later than one week after the start of classes of their first semester in order to allow them to add/drop courses, as necessary. Grades for these deficiency courses are recorded on the student’s undergraduate transcript and could impact a student's academic standing in their graduate program.

## Graduate Students in Undergraduate Courses

Students may take undergraduate courses of interest or deemed necessary to fully carry out thesis research. These courses cannot be used to fulfill the requirements for the degree, which must be 500-level and above.

## Undergraduate Students in Graduate Courses

With the consent of the student's department and the Dean of Graduate Studies, a qualified senior may enroll in 500-level courses without being a registered graduate student. At least a 2.5 GPA is required. Any undergraduate taking graduate-level credit must receive approval and agree to the specific terms selected.

· Students requesting the credits as undergraduate credits or those who do not qualify to have the credits listed on the graduate transcript must register for the course as UG (undergraduate credit). The credits will be listed on the undergraduate transcript and the credits will impact the undergraduate GPA.

· Students who request the credits as graduate-level credits and meet the qualifications to have the credits listed on the graduate transcript must register for the course as GR (graduate credit). The credits will be listed on the graduate transcript and the credits will impact the graduate level GPA.

· Once registered as UG or GR, the level cannot be changed after the add/drop date of the semester in which the course is taken.

· Students may apply up to 12 credits of unused graduate-level coursework, registered as GR, while enrolled as a full-time undergraduate student, toward a Mines graduate degree. For students in a combined program, these credits are in addition to the 6 credits being counted toward both the undergraduate and graduate degrees as double counted courses.

· Financial aid may be impacted. Email finaid@mines.edu for more information on financial aid impacts.

## Cross-Listed Courses

Only the graduate section of a 4xx/5xx cross-listed course can count toward a graduate degree or graduate certificate. Students may only receive credit for one section of a 4xx/5xx cross-listed course. For example, if a student received credit for the undergraduate section (4xx), the graduate section (5xx) cannot be taken for graduate credit. No more than 50% of the credits used to award a graduate degree can come from graduate sections of 4xx/5xx cross-listed courses.

## Absenteeism

### Introduction

Mines students are expected to fulfill their academic requirements through attendance and/or participation. Class attendance is required of all students unless the student has an excused absence granted by the school or the student's professor. Excused absences may be granted for five general reasons:

1. Student is unable to attend class due to unexpected and immediate physical or mental wellbeing concerns (illness, surgery, injury, mental health, or hospitalization). In this regard, the student is reasonably unable to attend class, or it is in the best interest of the student's health and/or the health of the Mines community for the student to be excused.
2. Student has a documented personal reason for the absence (e.g., jury duty, death in the immediate family, religious holiday or observance, etc.) or unforeseen, unavoidable, and anomalous conflict subject to review and approval.
3. Student is a sanctioned athlete and representing Mines in a sanctioned athletics activity per the Athletics Department.
4. Student is representing Mines in an authorized activity related to a club or academic endeavor such as: academic competitions, student professional society conferences, department-sponsored trip, authorized research opportunity or request, club sport competition, program-sponsored competitions, etc. Regularly scheduled and/or recurring commitments may not qualify.
5. Student is granted an excused absence through a sanctioned office because of protected, unexpected, sensitive, or time-sensitive circumstance(s). Sanctioned offices are Office for Institutional Equity (i.e., Title IX), SOS, DSS, Dean of Students Office/VPSA.

It is recognized that excused absences will occasionally occur, and faculty are expected to establish and clearly communicate the Excused Absence Policy and course-specific guidance or expectations in their course Syllabus.

Faculty may grant an excused absence for their own course upon request by a student.

Student requests for an excused absence does not guarantee approval. Students may be asked to provide documentation and the excused absence request is subject to approval by Student Life. Approval may consider all aspects of the request, including the duration of the request and nature of the request.

Opportunistic or habitual abuse of the excused absence policy violates the Mines Code of Conduct. Any patterns of absences that specifically result in missing exams/tests/quizzes may be investigated.

### Once an Excused Absence is Granted:

The University expects each student to be responsible for learning material missed because of an excused absence.

If the student missed an in-class graded activity because of their excused absence, the faculty have the following options:

1. Require that the activity be made up within a reasonable time frame based on the situation as determined by the faculty member.
2. Require that an alternative activity be completed within a reasonable time frame based on the situation as determined by the faculty member.
   a. If it is deemed necessary by the faculty to use an alternative activity, it should be comparable in terms of rigor and time of completion to the original activity in such a way that having missed the original activity will not penalize the student.
   b. The alternative activity should also align with the same learning objectives as the original graded activity.
3. Remove the graded activity from the student's overall grade calculation: If the faculty determines certain graded activities have pedagogical value which cannot be reasonably replicated, they will instead remove those graded activities from the student's overall grade calculation.

a. This will be separate from any grading adjustment(s) - including but not limited to dropping the lowest grade(s) - available to the rest of the class.

Any out-of-class graded activities that are due on the day of an excused absence may be accommodated. The details can be established by faculty based on the student situation or more generally in their course syllabus.

## Excessive Absences

A student can jeopardize their opportunity to gain and demonstrate course mastery with excessive absences.

Further, a student can jeopardize their academic status with an unreasonable number of removed graded activities. If the number of removed graded activities (defined as #3 from “Once an Excused Absence is Granted”) surpasses a reasonable threshold set by the faculty in the course Syllabus, then additional missed graded activities may not be removed, and the student may be advised to withdraw from the course or receive the subsequent and appropriate grade, which may include failure of the course.

Students should review the Incomplete and Complete Hardship or Medical Withdrawal Policies if they believe that these procedures may apply in their situation given excessive absences. Additional information on Withdrawals can be found here and information on incompletes can be found here.

Any student with chronic absences may be required to meet with Student Life to discuss resources available to them to reduce future absences.

## Unexcused Absences

All absences that are not documented as excused absences are considered unexcused absences. Faculty members may deny a student the opportunity to make up some or all work missed due to an unexcused absence(s). However, faculty members have discretion to grant a student permission to make up any missed academic work for an unexcused absence. The faculty member may consider the student’s class performance and attendance in the decision.

***Important Note:*** *Faculty will seek to honor all documented excused absences according to this policy and the course Syllabus. However, class attendance is essential to understand the material and for learning to take place. Excessive or opportunistic absences regardless of the reason may result in a reduced or failing grade in the course based on course content and delivery. As content and delivery differ among faculty and classes, it is important for a student missing class to discuss the absences, excused or unexcused, with his/her/their faculty member(s) to determine what will be considered excessive.*

## Withdrawing from School

To officially withdraw from Mines, a graduate student must submit a Withdrawal from Graduate School form to the Office of Graduate Studies. If the form is submitted by the add/drop date, the student will be dropped from all credits and receive a full refund. If the form is submitted after the add/drop date, the student will receive grades of W in courses in progress and will be charged the full tuition and fees (see the Payment and Refund section). If the student does not officially withdraw, the course grades are recorded as F’s and the student will be responsible for the tuition and fees due. Federal aid recipients should check with the Financial Aid office to determine what impact a withdrawal may have on current or future aid.

Students who leave school without submitting a Withdrawal from Graduate School form, but decide to return at a later date, will need to apply for admission and be readmitted.

PhD students planning to voluntarily withdraw from their doctoral program may potentially depart Mines with an earned master’s degree. Approval is subject to review of student academic performance, including earned credit for coursework and/or research. For more information on this potential pathway, students should speak with their faculty advisor or the Office of Graduate Studies. The Office of Graduate Studies is responsible for oversight and administration of this pathway. While the graduate dean ultimately approves the student request, all relevant parties including the faculty advisor and departmental or program leadership will be included. This option is not applicable to those seeking temporary leave from Mines.

# Graduate Grading System

## Grades

When a student registers for a graduate (500- and 600-level ) course, one of the following grades will appear on the academic record. Grades are based on the level of performance and represent the extent of the student's demonstrated mastery of the material listed in the course outline and achievement of the stated course objectives. These are Mines' grade symbols and their qualitative interpretations:

| Symbol | Interpretation |
|---|---|
| A | Acceptable for Graduate Credit |
| A- | Acceptable for Graduate Credit |
| B+ | Acceptable for Graduate Credit |
| B | Acceptable for Graduate Credit |
| B- | May be Acceptable for Graduate Credit |
| C+ | May be Acceptable for Graduate Credit |
| C | May be Acceptable for Graduate Credit |
| C- | May be Acceptable for Graduate Credit |
| D+ | Not Acceptable for Graduate Credit |
| D | Not Acceptable for Graduate Credit |
| D- | Not Acceptable for Graduate Credit |
| F | Failed |
| S | Satisfactory (C- or better, used as a mid-term grade) |
| U | Unsatisfactory (below C-, used as a mid-term grade) |
| INC | Incomplete |
| PRG | Satisfactory Progress |
| PRU | Unsatisfactory Progress |

Graduate students enrolled in undergraduate-level courses (400-level and below) are graded using the undergraduate grading system and coursework will be recorded on the undergraduate transcript.

In addition to these performance symbols, the following is a list of additional registration symbols that may appear on a Mines transcript:

| Symbol | Interpretation |
|---|---|
| WI | Involuntarily Withdrawn |
| W | Withdrew, No Penalty |
| T | Transfer Credit |
| NC | Not for Credit |
| Z | Grade not yet Submitted |

## Incomplete Grade

An Incomplete INC is a temporary grade which may be given at the instructor's discretion to a student when illness, necessary absence, or other reasons beyond the control of the student prevent completion of course requirements by the end of the academic term. An INC is restricted to cases in which the student satisfactorily completed a significant amount of the coursework, including attendance and participation.

The student and the instructor should discuss the terms for the incomplete before the end of the term. The instructor may grant up to one year, but the time limit may be less, to complete outstanding coursework. Any outstanding grade of INC will be converted to an F grade if it has not been updated by the instructor after one year. In the event that an INC grade remains on the record at the completion of the degree, the INC will be converted to an F and included in the final GPA.

## Satisfactory Progress Grades

A graduate student may receive a grade of Satisfactory Progress (PRG) in any one of three possible situations:

1. As a passing grade given in a course that is graded pass-fail.
2. As a grade for a course extending more than one semester.
3. As a grade indicating successful completion of research credit hours.

When applied to pass-fail courses, the Satisfactory Progress (PRG) grade indicates successful completion of the requirements of the course. A grade of Unsatisfactory Progress (PRU) as applied to pass-fail courses indicates the student failed to meet the requirements for successful completion of the course. The PRG and PRU grades have no point value toward a student's GPA. As described in the Unsatisfactory Academic Performance portion of this catalog, receipt of a PRU grade indicates unsatisfactory progress toward degree completion and will trigger academic disciplinary proceedings.

For students completing independent study or seminar courses extending over multiple terms, the progress grade has no point value. In such cases, the student receives a grade of PRG (progress). For multiterm independent study courses, upon completion of course requirements, a final letter grade is assigned in the last term in which the student enrolled in the course. In seminar courses in which continuous enrollment is required by the degree program, the PRG grade remains on all previous terms, with the option of either assigning a PRG grade or a final letter grade the last term of attendance.

When applied to research credits, the Satisfactory Progress (PRG) grade also has no point value toward a student's GPA, but indicates satisfactory progress toward completion of the research component of a student's thesis-based degree program. Alternatively, a grade of PRU, Unsatisfactory Progress, may be given, and if given, indicates that a student has not made satisfactory progress toward the research component of a thesis-based degree program. In this case, receipt of a grade of PRU may trigger academic disciplinary proceedings as described in the Unsatisfactory Academic Performance portion of this catalog.

Unless faculty submit the Change of Grade forms to the registrar, grades of PRU delivered for unsatisfactory research performance are not changed to PRG upon the successful completion of a student's degree program.

## NC Grade

For special reasons and with the instructor's permission, a student may register in a course for no credit (NC). To have the grade NC appear on the transcript, the student must enroll at registration time as an NC student in the course and comply with all conditions stipulated by the course instructor. If a student registered as NC fails to satisfy all conditions, no record of this registration in the course will be made.

## Quality Hours and Quality Points

For graduation, a student must successfully complete a certain number of required credits and must maintain grades at a satisfactory level. Numerical values assigned to each letter grade are given in the table below:

| Grade | Numerical Value |
|---|---|
| A | 4.000 |
| A- | 3.700 |
| B+ | 3.300 |
| B | 3.000 |
| B- | 2.700 |
| C+ | 2.300 |
| C | 2.000 |
| C- | 1.700 |
| D+ | 1.300 |
| D | 1.000 |
| D- | 0.700 |
| F | 0.000 |

The number of quality points earned in any course is the number of credit hours assigned to that course multiplied by the numerical value of the grade received. The quality (or grade-point average) hours earned are the number of credit hours in which grades are awarded. To compute a grade-point average, the number of cumulative quality hours is divided into the cumulative quality points earned. Grades of W, WI, INC, PRG, PRU, or NC are not counted in quality hours.

## Credit Hours

The number of times a class meets during a week (for lecture, recitation, or laboratory) determines the number of credit hours assigned to that course. Class sessions are normally 50 minutes long and represent one hour of credit for each hour meeting. A minimum of three hours of laboratory work per week is equivalent to one hour of credit. For the average student, each hour of lecture and recitation requires at least two hours of preparation.

## Grade-Point Averages

Grade-point averages (GPAs) shall be specified, recorded, reported, and used to three figures following the decimal point for any and all purposes to which said averages may apply.

All graduate degree programs require students to have a minimum overall grade point average of 3.0 in order to be eligible to receive the degree. All courses, including graduate courses taken as a non-degree graduate student and graduate-level courses taken at Colorado School of Mines after first enrolling in a graduate degree program are included in the calculation of the overall graduate grade-point average. Grades for courses applied to a degree program as transfer credit are not included in any grade-point average calculation. Specifics in calculating the overall GPA, and other grade-point averages, are defined below.

## Overall Grade-Point Average

The overall graduate level grade-point average includes all attempts at courses taken at Colorado School of Mines while a graduate student, whether degree seeking or non-degree, with the exception of courses that fall under the repeat policy described below.

If a course completed during the Fall 2023 term or after (1) is a repeat of a course completed in a previous term in which the student received a grade lower than a B, (2) was not already used for an awarded degree, and (3) is not repeatable for credit, the higher grade and credits earned will count toward the student's grade-point average and the student's degree requirements. The repeated course must be an exact match to the previous course completed (subject and number). A course that falls under this repeat policy may only be retaken once for the purpose of improving a student's grade point average.

Courses from other institutions transferred to Colorado School of Mines are not counted in any grade-point average and cannot be used under this repeat policy.

All occurrences of every course taken at Colorado School of Mines will appear on the official transcript along with the associated grade.

## Course and Research Grades

All candidates for graduate degrees must maintain a cumulative grade-point average of at least 3.0 in all courses taken at Mines and listed on the graduate transcript. This includes both graduate and undergraduate courses. Any grade lower than C- is not acceptable for credit toward graduate degree requirements.

For research credits, students receive either an "Satisfactory Progress" or an "Unsatisfactory Progress" grade based on their faculty advisor's evaluation of their work. Research grades do not enter into the calculation of the student's grade-point average.

Students who fail to maintain a grade-point average of at least 3.0, or who receive an Unsatisfactory Progress research grade are placed on academic probation by the graduate dean and may be subject to dismissal as defined by the Unsatisfactory Academic Performance section of this catalog.

## Grade Changes

After the completion of final grading for a term, only corrections to errors in grading may be processed and they must be for grade improvements only. Corrections to errors in grading for all students will be accepted one year from the original grade entry. With the exception of punitive disciplinary actions, diminution of a grade is not allowed without approval of the provost.

## Grade Appeal Process

Mines faculty have the responsibility and sole authority for assigning grades. As instructors, this responsibility includes clearly stating the instructional objectives of a course, defining how grades will be assigned in a way that is consistent with these objectives, and then assigning grades. It is the student's responsibility to understand the grading criteria and then maintain the standards of academic performance established for each course in which he or she is enrolled.

If a student believes he or she has been unfairly graded, the student may appeal this decision first to the instructor of the course, and if the appeal is denied, to the Academic Standards Committee of the Faculty Senate. The Academic Standards Committee is the faculty body authorized to review and modify course grades in appropriate circumstances. Any decision made by the Academic Standards Committee is final. In evaluating a grade appeal, the Academic Standards Committee will place the burden of proof on the student. For a grade to be revised by the Academic Standards Committee, the student must demonstrate that the grading decision was unfair by documenting that one or more of the following conditions applied:

1. The grading decision was based on something other than course performance, unless the grade was a result of penalty for academic dishonesty.
2. The grading decision was based on standards that were unreasonably different from those applied to other students in the same section of that course.
3. The grading decision was based on standards that differed substantially and unreasonably from those previously articulated by the instructor.

To appeal a grade, the student should proceed as follows:

1. The student should prepare an appeal of the grade received in the course. This appeal must define the basis for the appeal and must present all relevant evidence supporting the student's case.
2. After preparing the appeal, the student should deliver this appeal to the course instructor and attempt to resolve the issue directly with the instructor. Written grade appeals must be delivered to the instructor no later than 10 business days after the start of the regular (fall or spring) semester immediately following the semester in which the contested grade was received. In the event that the course instructor is unavailable because of leave, illness, sabbatical, retirement, or resignation from the university, the course coordinator (first) or the department head/program director (second) shall represent the instructor.
3. If after discussion with the instructor, the student is still dissatisfied, he or she can proceed with the appeal by emailing a copy of the appeal and a copy of a summary of the instructor/student meetings held in connection with the previous step to the Academic Standards Committee. All information must be submitted to the committee no later than 25 business days after the start of the semester immediately following the semester in which the contested grade was received.
4. On the basis of all information deemed pertinent to the grade appeal, the Academic Standards Committee will determine whether the grade should be revised. The decision rendered will be either:
   a. the original grading decision is upheld, or
   b. sufficient evidence exists to indicate a grade has been assigned unfairly.

In the latter case, the Academic Standards Committee will assign the student a new grade for the course. The committee's decision is final. The decision and supporting documentation will be delivered to the Faculty Senate, the office of the executive vice president for Academic Affairs, the student, the instructor, and the instructor's department head/program director no later than 25 business days following the Faculty Senate's receipt of the grade appeal.

The schedule, but not the process, outlined above may be modified upon mutual agreement of the student, the course instructor, and the Academic Standards Committee.

# Graduation

## All students expecting to graduate must apply to graduate.

Graduation application deadlines are scheduled well in advance of the date of commencement to allow time for commencement preparation. Students who submit applications after the stated deadline cannot be guaranteed a diploma dated for that graduation, and cannot be assured inclusion in the graduation program or ceremony. Graduation applications are accepted only for students who have previously submitted to and had approved by the Office of Graduate Studies the appropriate advisor/thesis committee (thesis students only), Degree Audit form (all students), and Admission to Candidacy form (PhD candidates only) as applicable to the degree sought. Students earning more than one degree must submit the appropriate forms for each degree and apply to graduate for each degree.

## Graduation Requirements

**Registration**

To graduate, students must be registered during the term in which they complete their program.

An exception to this registration policy allows students to complete an early checkout in the spring graduation semester if all requirements have been successfully met by a particular deadline.

For additional information, refer to https://www.mines.edu/graduate-studies/graduation-deadlines/.

**Check-out**

All graduating students must officially check out of their degree program. Students will be enrolled in a graduation check-out course after the student has applied to graduate. Students must follow the directions and complete the course by the established deadline.

**Awarding Degrees**

The awarding of a degree is contingent upon the student's successful completion of all program requirements with at least a 3.000 cumulative GPA before the date of graduation. Students who fail to graduate at the time originally anticipated must reapply for the next graduation before the appropriate deadline date stated on the Graduate School webpage.

Students who have completed all their degree requirements at least four weeks prior to the standard checkout deadline for their graduation date can, if necessary, request a letter from the Graduate Office certifying the completion of their programs. The student must have applied to graduate for the current or next graduation, met all the degree requirements, and have no holds. Note, the diploma and transcripts will show the date of the actual graduation, and the degree will not show as being awarded until after degrees have been awarded for that term.

Degrees for all students will be awarded within 10 business days after the commencement ceremony of the term in which the student applied to graduate, or for August graduates, 10 business days after the last day of the full summer term.

**Commencement**

Commencements are held in December and May. Students graduating in August may walk in the December graduation ceremony. Students eligible to graduate at these times are expected to attend their respective graduation exercises and must apply to graduate by the stated deadlines to be eligible to walk in the appropriate commencement ceremony. Students who do not apply to graduate by the stated deadlines may not be allowed to walk in the commencement ceremony. The exception is that non-thesis students graduating in August may be allowed to walk in the May ceremony if all of the following are met: the student has fewer than 6 credits to complete in the summer; the student has applied to graduate in May; and the student has consulted with the Mines Commencement Director about the exception. Students in thesis-based degree programs may not participate in graduation ceremonies before completing all degree requirements. Questions should be directed to commencement.mines.edu/.

**Diplomas, Certificates, Transcripts, and Letters of Completion**

Diplomas, certificates, transcripts, and letters of completion will not be released by the school for any student or graduate who has an unsettled obligation of any kind to the school. Diplomas and transcripts will be available through the Registrar's Office after degrees have been awarded. Students who check out early may request a Letter of Completion from the Graduate Office, but these letters will only be sent if requested at least four weeks prior to the commencement ceremony. Requests for a Letter of Completion after that time will not be accepted, so students will need to order the diploma or transcripts, as needed.

# Independent Studies

To register for an independent study course, a student must get the appropriate form from the Registrar's Office, have it completed by the instructor involved and appropriate department head, and return it to the Registrar's Office. The form must be submitted no later than the Census Day (last day of registration) for the term in which the independent study is to be completed.

For each semester credit hour awarded for independent study (x99 course), a student is expected to invest approximately 25 contact hours plus 30 hours of independent work. Additionally, the faculty certifies that an appropriate course syllabus has been developed for the course, reviewed by the department or program, and the student, and is available upon request from the department or program.

| Credit Hours | Instructor Contact Hours | Independent Work Hours | Total Hours | Hours Per Week |
|---|---|---|---|---|
| 1.0 | 25.0 | 30.0 | 55.0 | 3.7 |
| 2.0 | 50.0 | 60.0 | 110.0 | 7.3 |
| 3.0 | 75.0 | 90.0 | 165.0 | 11.0 |
| 4.0 | 100.0 | 120.0 | 220.0 | 14.7 |

| | | | | |
|---|---|---|---|---|
| 5.0 | 125.0 | 150.0 | 275.0 | 18.3 |
| 6.0 | 150.0 | 180.0 | 330.0 | 22.0 |

# Non-Degree Students

A non-degree student is one who has not applied to pursue a degree program at Mines but wishes to take courses regularly offered on campus. Non-degree students register for courses through the Registrar's Office after degree-seeking students have registered. Such students may take any course for which they have the prerequisites as listed in the Mines Catalog or have the permission of the instructor. Transcripts or evidence of the prerequisites are required. Non-degree students pay all applicable tuition and student fees. Non-degree students are not eligible for financial aid.

Courses completed while the student is a non-degree graduate student count toward the overall graduate-level grade-point average on the Mines transcript.

For more information, please view the Non-Degree Program Requirements section of the Graduate Admissions Requirements webpage.

# Public Access to Graduate Thesis

The award of a thesis-based graduate degree is conditioned on the student uploading their completed thesis in the Electronic Thesis and Dissertation system to ensure its availability to the public. Although the student retains the copyright in the thesis, by uploading the thesis in the electronic system, the student assigns a perpetual, non-exclusive, royalty-free license to Mines to permit Mines to copy the thesis and allow the public reasonable access to it.

Under special circumstances, Mines may agree to include proprietary research in a graduate student's thesis. The nature and extent of the proprietary research reported in the thesis must be agreed upon in writing by the principal investigator and the student, and must be specified when the thesis or dissertation is uploaded into the electronic system.

In some cases, the proprietary nature of the underlying research may require the school to delay public access to the completed thesis for a limited period of time. In no case will public access to the thesis be denied for more than 12 months from the date the thesis or dissertation is published by the electronic system.

# Unsatisfactory Academic Performance

## Unsatisfactory Academic Progress Resulting in Probation or Discretionary Dismissal

A student's progress toward successful completion of a graduate degree shall be deemed unsatisfactory if any of the following conditions occur:

- Failure to maintain a cumulative grade-point average (GPA) of 3.0 or greater (see Graduate Grading System section);
- Receipt of an Unsatisfactory Progress (PRU) grade for research; or
- Receipt of an Unsatisfactory Progress recommendation from the following:
  - the department head or program director.
  - the student's thesis committee.
  - a departmental committee charged with the responsibility of monitoring the student's progress.

Unsatisfactory academic progress on the part of a graduate student shall be reported to the graduate dean in a timely manner at the end of each semester. Students making unsatisfactory progress by any of the measures listed above are subject to discretionary dismissal according to the procedure outlined below.

In addition, students in thesis-based degree programs who are not admitted to candidacy within the time limits specified in this catalog may be subject to immediate mandatory dismissal according to the procedure outlined below. Failure to fulfill this requirement must be reported to the graduate dean in a timely manner by the department head or program director.

## Probation and Discretionary Dismissal Process and Procedure

The process described in this section is based on full-time enrollment. At the discretion of the graduate dean, the academic standing of a part-time student may be evaluated in terms of the credit equivalent of a semester of full-time enrollment.

**Probation**

The first semester of unsatisfactory performance will result in the student being placed on academic probation. The student will be notified by the graduate dean and asked to consult with their advisor. The notation on the student's transcripts will indicate that the student is on probation. To have the probation notation removed from the transcript, the student must resolve the issue that caused the academic probation (i.e., bring their cumulative GPA to a 3.0 or above, obtain a satisfactory, or PRG, grade for research instead of a second PRU, or address the issue from the department) in the subsequent semester. Students who do not resolve the issue in the subsequent semester will have the academic probation notation remain on the transcript.

**Discretionary Dismissal**

The second semester on academic probation (not necessarily a consecutive semester) will result in the initiation of a discretionary dismissal process. The graduate dean will notify the student in a timely manner and invite them to consult with their advisor and submit a written remedial plan, including performance milestones and deadlines, to correct the deficiencies that caused or contributed to the student's unsatisfactory progress in coursework and/or research. The remedial plan, which must be approved by the student's faculty advisor and the department head or program director, shall be submitted to the dean no later than 10 business days from the date of official notification to the student of the potential discretionary dismissal. If the dean concludes that the remedial plan is likely to lead to the restoration of satisfactory performance and/or successful completion of all degree requirements within an acceptable time frame, the dean may halt the discretionary dismissal process and allow the student to continue working toward their degree. If the dean concludes that the remedial plan is inadequate, or that it is unlikely to lead to successful completion of all degree requirements within an acceptable time frame, the dean will notify the student of their discretionary dismissal and inform the student of their right to appeal the dismissal as outlined below. The academic probation notation will remain on the transcript during the time frame of the plan and will be removed if the plan is successful.

If the student fails to meet the conditions of the remedial plan, the student will be subject to mandatory dismissal.

## Unsatisfactory Academic Performance Resulting in Mandatory Dismissal

Unsatisfactory performance as gauged by any of the following measures shall result in immediate, mandatory dismissal of a graduate student:

1. Failure to successfully defend the thesis after two attempts.
2. Failure to be admitted to candidacy.
3. Failure by a student subject to discretionary dismissal to achieve a performance milestone or meet a deadline contained in their remedial plan.

The graduate dean shall be notified promptly of any situation that may subject a student to mandatory dismissal. In this event, the dean shall notify the student of their dismissal and inform the student of their right to appeal the dismissal as outlined below.

Students who have been notified of mandatory dismissal will have 10 business days to submit an appeal based on the existence of extenuating circumstances or withdraw from their graduate program.

Students who have an appeal for extenuating circumstances approved by the faculty committee will be reinstated in the same degree program and will be allowed to continue with their graduate studies. If an appeal is denied, the dismissal will stand.

Students who withdraw or are dismissed may request readmission to either the same program or a different degree program by submitting a full application for admission to Graduate Admissions. The application will be reviewed through the normal admission process. To return, the student will need to be readmitted into a degree program.

If a student who has been reinstated or readmitted to their former degree program is subsequently found to be making unsatisfactory progress, the student will immediately be subject to mandatory dismissal.

## Appeal Procedures

Both mandatory and discretionary dismissals may be appealed by a graduate student pursuant to this procedure. To trigger review hereunder, an appeal must:

1. Be based on the documented existence of extenuating circumstances and/or irregularities in process. Examples of extenuating circumstances and/or irregularities in process along with documentation and details can be found on the Graduate Student Dismissal Appeal form on the Office of Graduate Studies webpage.
2. Be submitted using the Graduate Student Dismissal Appeal form.
3. Include a description of the matter being appealed, supporting documentation, and a plan for successful completion of the degree program.
4. Be filed with the Office of Graduate Studies, c/o the graduate dean, no later than 10 business days from the date upon which the student received official notification from the dean regarding their dismissal.

Upon receipt of a timely appeal of a discretionary or mandatory dismissal, the graduate dean will review the stated grounds for the appeal. If the dean determines that the appeal satisfies the conditions required for review, the dean will request that the Faculty Senate appoint a review committee comprised of three tenured faculty members who are not members of the student's home or minor (if applicable) department or program. The review committee shall review the student's appeal and issue a written recommendation thereon to the dean within 10 business days. During the course of performing this function, the committee may:

1. Interview the student, the student's advisor, and if appropriate, the student's thesis committee.
2. Review all documentation related to the appeal under consideration.
3. Secure the assistance of outside expertise, if needed.
4. Obtain any other relevant information necessary to properly consider the appeal.

If the dean determines that the appeal submitted does not have the required documentation showing sufficient extenuating circumstances, then the appeal will not be accepted and the student's dismissal will stand.

The authority to render a final decision regarding all graduate student appeals filed hereunder shall rest with the graduate dean.

# Exceptions and Appeals

## Academic Policies and Requirements

Academic policies and requirements are included in the catalog on the authority of the Mines Board of Trustees as delegated to the Faculty Senate. These include matters such as degree requirements, grading systems, thesis and dissertation standards, admission standards, new and modified degree programs, certificates, minors and courses. No Mines administrator, faculty, or staff member may change, waive, or grant exceptions to such academic policies and requirements without approval of the Graduate Council, the Senate, and/or the Board of Trustees as appropriate.

## Administrative Policies and Procedures

Administrative Policies and Procedures are included in this catalog on the authority of the Mines Board of Trustees as delegated to the appropriate administrative office. These include, but are not limited to, matters such as student record keeping, thesis and dissertation formats and deadlines, registration requirements and procedures, assessment of tuition and fees, and allocation of financial aid. The graduate dean may waive or grant exceptions to such administrative policies and procedures as warranted by the circumstances of individual cases.

Any graduate student may request a waiver or exception by the following process:

1. Contact the Office of Graduate Studies to determine whether a standard form exists. If so, complete the form. If a standard form does not exist, prepare a memo with a statement of the request and a discussion of the reasons why a waiver or exception would be justified.
2. Have the memo or the form approved by the student's advisor and department head or program director, then submit it to the graduate dean.
3. If the request involves academic policies or requirements, the graduate dean will request Graduate Council approval at the council's next regularly scheduled meeting.
4. The graduate dean will notify the student of the decision. The student may file a written appeal with the provost within 10 business days of being notified of the decision. The provost will investigate as appropriate the issue under consideration and render a decision. The decision of the provost is final.

5. At the next graduate council meeting, the dean will notify the Graduate Council of the request, the decision and the reasons for the decision. If the Graduate Council endorses the decision, then any other student in the same situation having the same justification can expect the same decision.

# Tuition, Fees, Financial Assistance

Tuition and fees are established by the Board of Trustees of Colorado School of Mines following the annual budget process and action by the Colorado General Assembly and governor.

## Tuition

The official tuition and approved charges for the academic year will be available prior to the start of the academic year and can be found online on the bursar's webpage.

## Fees

The official fees, approved charges, and fee descriptions for the academic year will be available prior to the start of the academic year and can be found online on the bursar's webpage.

## Payments and Refunds

### Financial Responsibility

It is the student’s responsibility to abide by Mines payment and refund policies when registering for classes.

- Full payment of tuition and fees are due by 4 p.m. MST on the first business day following Census Day for each term. Please see the bursar's webpage for specific semester information.
- Students are responsible for viewing their account balance online through Trailhead. Mines generates electronic invoices only; no paper invoices will be mailed.
- Students are responsible for dropping their courses by the published drop deadline if they don’t plan to attend. Failure to do so will result in charges incurred on the student account.

### If you don’t fulfill your financial obligations:

- At 4 p.m. MST on the due date, any unpaid balance will be assessed a 1.5% late fee.
- An additional 1.5% late fee will be assessed to any unpaid balance each month thereafter.
- Accounts not paid in full by the last day to drop classes are considered past due. Holds will be placed on past due accounts preventing registration, transcripts, diplomas, and access to other student records.
- Accounts not paid in full at the end of each semester are considered delinquent. Delinquent accounts will be turned over to a collections agency in accordance with Colorado law, and all collection fees and costs will be added to the account balance. The collection agency may report delinquent accounts to the national credit bureau.
- Students whose accounts have been sent to a collection agency must pay their balance in full and prepay for any subsequent semester before registration will be allowed.
- Any students whose debt to Mines was written off due to a bankruptcy discharge will be required to prepay for future semesters before registration will be allowed.

### Refunds

The amount of tuition and fee assessments is based primarily on each student's enrolled courses. In the event a student withdraws from a course or courses, assessments will be adjusted as follows:

- If withdrawal from a course or courses is made prior to the end of the add/drop period for the term of enrollment, as determined by the registrar, tuition and fees will be adjusted to the new course level without penalty.
- If withdrawal from a course or courses is made after the add/drop period, regardless of whether the student officially withdraws from Mines, no adjustments in charges will be made.

Please note: students receiving federal financial aid under the Title IV programs may have a different refund as required by federal law or regulations.

Room and board refunds are pro-rated to the date of checkout from the residence hall. Arrangements must be made with the Housing Office.

Student health insurance charges are not refundable. The insurance remains in effect for the entire semester.

## Financial Assistance for Graduate Studies

Graduate study is a considerable investment of time, energy, and money by serious students who expect a substantial return not only in satisfaction but also in future earnings. Applicants are expected to weigh carefully the investment they are willing to make against expected benefits before applying for admission.

Students are also expected to make full use of any resources available, including personal and loan funds, to cover expenses, and the school can offer some students financial aid through graduate research and teaching assistantships and through industry, state, and federal fellowships.

## Purpose of Financial Aid

The Graduate School’s limited financial aid is used

1. To give equal access to graduate study by assisting students with limited personal resources.
2. To compensate graduate students who teach and do research.
3. To give an incentive to exceptional students who can provide academic leadership for continually improving graduate programs.

## Employment Restrictions and Agreements

Students who are employed full time or who are enrolled part-time are not eligible for financial aid through the Graduate School.

Students who are awarded assistantships must sign an appointment agreement, which gives the terms of appointment and specifies the amount and type of work required. Graduate assistants who hold regular appointments are expected to devote all their efforts to their educational program and may not be otherwise employed without the written permission of their supervisor and the graduate dean. Students with assistantships during the academic year must be registered as full time. During the summer session, they must be registered for a minimum of 3 credit hours, unless they qualify for a summer research registration

exception. Please see https://www.mines.edu/graduate_admissions/ for details on summer registration exception eligibility.

## Aid Application Forms

New students interested in applying for financial aid are encouraged to apply early. Financial aid forms are included in Graduate School application packets and may be filled out and returned with the other application papers.

## Graduate Fellowships

The departments and programs may award fellowships based on the student's academic performance.

## Graduate Student Loans

Federal student loans are available for graduate students who need additional funding beyond their own resources and any assistantships or fellowships they may receive. The Free Application for Federal Student Aid (FAFSA) must be completed to apply for these loan funds. Students must be degree-seeking graduate students, taking courses toward their degree, and attending at least part-time (4.5 hours) per semester (including summer) to be eligible. Degree-seeking students who are approved for reduced registration (4 hours/semester fall and spring and 3 hours summer) are also eligible. Students seeking a certificate or taking undergraduate courses to prepare them for graduate courses are not eligible.

Financial aid is only able to pay towards courses that will count towards a student current degree program. Students must be enrolled in at least half-time in those courses to be eligible for aid.

Specific information and procedures for filing the FAFSA can be found on the Financial Aid Office web site at https://finaid.mines.edu/. The Financial Aid Office telephone number is 303-273-3301, and the email address is finaid@mines.edu.

## Satisfactory Academic Progress for Federal Student Loans and Colorado Grad Grant

Students receiving assistance from federal or Colorado funds must make satisfactory academic progress toward their degree. Satisfactory progress is defined by maintaining adequate pace toward graduation and maintaining a 3.0 cumulative GPA at all times. The pace is measured by dividing the overall credit hours attempted by the overall credit hours completed. Students will be required to maintain a 75% completion rate at all times. Satisfactory standing is determined after each semester, including summer. If students are deficient in either the pace or grade-point average measure, they will receive a one-semester warning period during which they must return to satisfactory standing.

If this is not done, their eligibility will be terminated until such time as they return to satisfactory standing. Financial aid eligibility termination may be appealed to the Financial Aid Office on the basis of extenuating or special circumstances having negatively affected the student's academic performance. If approved, the student will receive a probationary period of one semester to regain satisfactory standing.

The deadline to apply to graduate and participate in commencement is the first day of the term in which the student intends to graduate/participate.

Any request to be added to the graduation list and/or commencement ceremony after this date may be made in writing and will be considered by the Office of Graduate Studies. If the request is denied, the student will be required to apply for the next available graduation/ceremony.

# General Requirements

Colorado School of Mines offers several certificate and degree programs for those who have completed an undergraduate degree program. These programs lead to the awarding of post-baccalaureate certificates, graduate certificates, professional master's degrees, thesis and non-thesis master of science degrees, non-thesis master of engineering degrees, and doctor of philosophy degrees. This section describes these certificates and degrees and explains the minimum institutional requirements for each. Students may apply to, and be admitted in, multiple graduate programs simultaneously. In this case, a student may use the same graduate course credits to satisfy the requirements for each certificate or degree.

Students enrolled simultaneously and/or sequentially in two Mines master's degree programs may use up to half of the course credits required for the master's degree program with the smallest course credit-hour requirement toward both degree programs. Before the Office of Graduate Studies will count these credits toward each degree requirement, the student must obtain written permission to do so from each department or program granting the degree. This permission should be submitted with the student's Degree Audit form and should clearly indicate that each degree program is aware that the specific credits are being counted toward the requirements of multiple master's degrees. For thesis-based students this permission should be provided by the student's thesis committee and department head or program director. For non-thesis and certificate programs, permission should be obtained from advisors and department head or program director.

Students simultaneously and/or sequentially enrolled in a master's degree and doctoral degree may, with departmental approval, count course credits toward each degree without limit. Approval to count credits toward a master's degree and doctoral degree will be indicated by the committee's and department head's or program director's signature on the Degree Audit form.

Course credits may never be applied toward more than three graduate degrees.

### Navigate to:


- Responsible Conduct of Research Requirement (p. 22)
- Professional Programs (p. 23)
- Master of Science and Master of Engineering Programs (p. 24)
- Doctor of Philosophy (p. 26)
- Roles and Responsibilities of Committee Members and Students (p. 28)


# Responsible Conduct of Research Requirement

All students supported at any time in their graduate career through the National Science Foundation (NSF) or the National Institutes of Health (NIH), as research assistants, hourly employees or fellowship awardees, must complete training in the responsible conduct of research (RCR). This requirement is in addition to all other institutional and program requirements described below and in the appropriate program sections of this catalog.

To satisfy the RCR requirement students must complete one of the following options:

- HASS565 – Option available to all students
- SYGN502 – Option available to all students
- Chemistry Program Option – Option available only to students in the chemistry program
- Physics Program Option: Option available only to students with physics faculty advisors or co-advisors
- Chemical and Biological Engineering (CBE) Option – Option available only to students in the CBE degree program

For additional information on program-specific options, contact the program.

By whatever means chosen, the NSF/NIH-RCR requirement must be completed prior to a candidate submitting the Degree Audit form. Students and advisors certify successful completion of the RCR requirement on the Degree Audit form.

# Professional Programs

## A. Post-Baccalaureate Certificate and Graduate Certificate Programs

Post-baccalaureate certificate and graduate certificate programs at Mines are designed to have selective focus, short time to completion and consist of coursework only. The two are distinguished by the amount of undergraduate-level coursework constituting the program. In general, graduate certificate programs consist of only graduate level coursework (500-level and above). Post-baccalaureate certificate programs can include courses at both the undergraduate and graduate level. For more information about specific certificate programs, please refer to the sections Departmental Graduate Programs and Interdisciplinary Graduate Programs of this catalog.

### 1. Academic Requirements

Post-baccalaureate certificates and graduate certificates require a minimum of 9 total credits. Specific credit requirements are detailed within the sections Departmental Graduate Programs and Interdisciplinary Graduate Programs of this catalog. Students may not, on an individual basis, request credits be transferred from other institutions as part of the certificate requirements. Some certificates, however, may allow the application of specific, pre-approved transfer credits or credits from other institutions with whom Mines has formal agreements for this purpose toward fulfilling the requirements of the certificate. All courses applied to a specific certificate are subject to approval by the program offering the certificate.

If a student has earned either a post-baccalaureate certificate or a graduate certificate and subsequently applies and is accepted into a master's or PhD program at Mines, credits earned in the certificate program may, with the approval of the advanced degree program, be applied to the advanced degree subject to all the applicable restrictions on credits that may be applied toward fulfilling the requirements of the advanced degree.

### 2. Graduation Requirements

A list of prerequisites for each post-baccalaureate or graduate certificate, if required, will be published by each program. If a student is admitted with deficiencies, the appropriate department head or program director will provide the student with a written list of courses required to remove these deficiencies. This list will be given to the student no later than one week after the start of classes of their first semester in order to allow for adding/dropping courses as necessary.

Upon completion of certificate requirements, a student must complete the graduation checkout course by the posted deadlines.

## B. Professional Master's Program

Mines awards specialized, career-oriented non-thesis master's degrees with the title of professional master (descriptive title). These are custom-designed degrees, each with a curriculum meeting the career advancement needs of a particular group of professionals in a field that is central to Mines' mission. For more information about these programs, please refer to the sections Departmental Graduate Programs and Interdisciplinary Graduate Programs of this catalog.

### 1. Academic Requirements

Each professional master's degree consists of a minimum of 30 total credits. Students must complete at least 21 credits at Mines in the degree program. The remaining credits may be transferred into the program. Requests for transfer credit must be approved by the faculty according to a process defined by the student’s home department or program. Transfer credits must not have been used as credit toward a bachelor's degree. The transfer limit includes Mines online courses. Up to 6 credits of special topics, independent study, or internship may be in the form of project credits done on the job as an employee or as a graduate intern. If project credits are to be used, the project proposal and final report must be approved by a Mines faculty advisor, although direct supervision may be provided by the employer. Students must maintain a cumulative grade-point average of 3.0 or better in Mines coursework.

### 2. Graduation Requirements

Full-time students must complete the following requirement within the first calendar year after enrolling in a professional master's degree program:

- Complete all prerequisite and core curriculum course requirements of their program.

If students are admitted with deficiencies, the appropriate department heads or program directors will provide the students written lists of courses required to remove the deficiencies. These lists will be given to the students no later than one week after the start of classes of their first semester in order to allow them to add/drop courses as necessary. Completion of prerequisites and deficiencies will be monitored by the department.

Upon completion of the above defined requirements, students must submit a Degree Audit form documenting satisfactory completion of the core curriculum requirements. Deficiency and/or prerequisite courses may not be listed on the Degree Audit form. The form must have the written approval of all members of the advisor and thesis committee, if appropriate.

To graduate, all professional master students must submit all required forms and complete the graduation checkout course by the posted deadlines.

# Master of Science and Master of Engineering Programs

## A. General Requirements

Graduate study at Mines can lead to one of a number of thesis and non-thesis-based master's degrees, depending on the interests of the student. All master's degree programs share the same academic requirements for grades and definition of minor programs.

### 1. Academic Requirements

A master's degree at Mines requires a minimum of 30 total credits, with some degrees requiring additional credits. As part of this minimum 30 credits, departments and programs are required to include a research or design experience supervised by Mines faculty. For more information about the specific research/design requirements, please refer to the appropriate department/program section of this catalog.

For non-thesis master's degrees, students must complete at least 21 credits at Mines in the degree program. All other coursework credits may be completed as transfer credits into the degree program. For thesis master's degrees, no more than 9 coursework credits may transfer.

The transfer credit limit includes any credits taken at another university, including credits taken under the Exchange Reciprocal Agreement. Transfer credits must not have been used as credit toward a bachelor's degree, must not be prerequisites or deficiencies, must have a letter grade of C or better, must be graduate-level credits and must be required for the degree. Requests for transfer credit must be approved by the faculty according to the process defined by a student's home department or program. All credits applied toward the degree, except transfer credits, must be earned at Mines. Students must maintain a cumulative grade-point average of 3.0 or better in Mines coursework.

### 2. Minor Programs

Students may choose to have a minor program or programs at the master's level. A minor program may not be taken in the student's major area of study. A designated minor requires a minimum of 9 credits of graduate coursework and must be approved by the student's advisor, home department head or program director, and a graduate faculty representative of the minor area of study. Fewer than half of the credits applied toward the minor degree program may be in the form of transfer credits. Transfer credits applied toward the minor are included as part of the overall transfer limitation applied to the degree as defined above.

### 3. Graduation Requirements

Within one calendar year of enrolling in the master's degree program, full-time students must complete the following requirements:

- Have a thesis committee appointment form on file in the Office of Graduate Studies (thesis-based students only).
- Complete all prerequisite and core curriculum course requirements of their department or program.

If students are admitted with deficiencies, the appropriate department heads or program directors will provide the students written lists of courses required to remove the deficiencies. These lists will be given to the students no later than one week after the start of classes of their first semester in order to allow them to add/drop courses as necessary. Completion of prerequisites and deficiencies will be monitored by the department.

Upon completion of the above-defined requirements, students must submit a Degree Audit form documenting satisfactory completion of the core curriculum requirements.* Deficiency and/or prerequisite courses may not be listed on the Degree Audit form. The form must have the written approval of all members of the advisor and thesis committee, if appropriate.

* Depending on the admit term, some students may not need to submit a Degree Audit form. Students who do not need to submit a Degree Audit form will be notified the first semester of study. Students who do not need to submit a Degree Audit form will, however, need to submit a form to transfer credits, double count credits, and/or substitute courses.

To graduate, all master of science and master of engineering students must submit all forms and complete the graduation checkout by the posted deadlines. In addition, thesis-based students must submit a signed Thesis Defense form, upload a content-approved thesis, and have the formatting approved by the posted deadlines.

## B. Non-Thesis Option

Non-thesis master's degrees (both non-thesis master of science and master of engineering) are offered by a number of departments and programs. See the specific department/program section of this catalog for more information. Although non-thesis master's students are not assigned a thesis committee, students in this program are assigned a faculty advisor by the student's home department or program. The advisor is subject to approval by the Office of Graduate Studies.

### 1. Internships – Course Credit

Students in non-thesis master of science and master of engineering degree programs can earn academic credit toward their degree for a paid internship. The 3-credit course, SYGN 598I, must be used as an elective to meet the total credit requirement for the degree, as determined by a degree audit. As a letter-graded, 3-credit course, the paid internship must be a minimum of 165 hours during the registration term (e.g., sixteen-week semester or eight-week part-of-term). The internship site and project must be approved by the student's advisor and department/program in advance and learning goals must be developed and discussed with the student. The Internship Form is available from the Office of Graduate Studies.

### 2. Internships - Curricular Practical Training (CPT)

- International students on F1 or J1 visa must have completed two semesters in full-time status to be eligible to apply for authorization to participate in an internship and register for SYGN 598I. F1 students must apply and be approved for CPT before they can participate in any internship activity. J1 students must apply and be approved for academic training before they can participate in any internship activity.
- All international students must receive approval from their advisor and department/program, then submit the Internship form to the Office of Graduate Studies (OGS) for review before submitting their application for CPT or academic training to ISSS.
- International students on F1 visa must maintain full time status while on CPT in fall and spring terms.

## C. Thesis Option

Thesis-based master of science degrees require completion of a satisfactory thesis and successful oral defense of this thesis. Academic

credit toward completion of the thesis must include successful completion of no fewer than 6 credits of master's-level research credit. The thesis is expected to report on original research that results in new knowledge and/or techniques or on creative engineering design that applies state-of-the-art knowledge and techniques to solve an important problem. In either case, the thesis should be an exemplary product that meets the rigorous scholarship standards of Colorado School of Mines. The student's faculty advisor and the master's thesis committee must approve the program of study and the topic for the thesis. The format of the thesis must comply with the appropriate guidelines promulgated by the Office of Graduate Studies.

## 1. Faculty Advisor Appointment

When admitted, each thesis-based master's student is assigned a faculty advisor by the department or program. Students who are assigned temporary advisors at admissions will work with their department or program to have a permanent advisor assigned. Master's students changing a temporary advisor to a permanent advisor or selecting a new advisor will need the new faculty advisor approved by the Office of Graduate Studies by the end of the second semester at Mines.

Advisors will provide advice regarding the student's thesis direction, research, and selection of courses. To be approved by the Office of Graduate Studies, advisors must be designated as Mines graduate faculty. Please refer to the Faculty Handbook for a definition of what constitutes Mines Graduate Faculty. Upon approval by the graduate dean, adjunct faculty, teaching faculty, visiting professors, emeritus professors, and off-campus representatives may be designated additional co-advisors.

The department head or program director of the degree program, and the graduate dean, must approve all faculty advisor appointments.

## 2. Thesis Committee

*The appointment status of faculty who can serve as voting members of a master's thesis committee was pending final approval by the Board of Trustees as of the date of publication of this catalog. Check with the Office of Graduate Studies for an update to the membership information provided below and if a catalog addendum is available.*

The graduate dean will approve a thesis committee whose members have been recommended by the student, the student's faculty advisor, and the student's department head/program director and whose members meet the minimum requirements listed below. Students should have a thesis committee approved by the end of their second semester.

This committee will have a minimum of three voting members, including the student's advisor, who are familiar with the student's area of study.

1. Of these three committee members, the first member will be the student's advisor. The advisor must be a full member of the graduate faculty.
2. The second member must be designated as either a full or associate member of the graduate faculty and knowledgeable in the technical areas of the thesis. The committee members acts as the thesis committee chairperson.
3. The third member of the committee may be a full or associate member of the graduate faculty or an off-campus member.
    - Off-campus members can be assigned to the committee as the third member or as additional members. If assigned as the third member, the member must be a voting member.
    - Off-campus members nominated for voting status on the Committee Request form must include a brief resume of their education and/or experience that demonstrates their competence to judge the quality and validity of the thesis. Such members also must agree to assume the same responsibilities expected of on-campus committee members including, but not limited to, attendance at committee meetings, review of thesis proposals, and drafts and defense.
4. Additional members (more than the three required), either from Mines or off-campus, may serve either with full voting status or in a nonvoting capacity. Mines members with voting status must meet the same criteria as those of required committee members. Off-campus members with voting status assume all responsibilities of on-campus committee members with respect to attendance of committee meetings, review of thesis drafts, participation in oral examinations, and thesis defense sessions.
5. If a thesis co-advisor is assigned, this individual, Mines faculty or off-campus member, becomes a fourth required member of the committee. Co-advisors must be voting members of the committee.
6. If a minor field is designated, an additional committee member must be included who is an expert in that field. Minor representatives must be Full or Associate Members of the Graduate Faculty who are participating faculty in the minor program area. If multiple minor programs are pursued, each must have a committee representative as defined above.
7. A thesis committee chairperson is designated at the time the student requests the formation of the thesis committee. The chairperson is responsible for leading all meetings of the thesis committee and for directing the student's thesis defense. The second or third member, not the advisor or co-advisor, must serve in the role of committee chair. The committee chair must be Mines faculty and cannot be off-campus or adjunct/affiliate faculty.

Shortly after its appointment, the committee will meet with the student to hear a presentation of the proposed course of study and thesis topic. The committee and the student must agree on a satisfactory program and the student must obtain the committee approval of the written thesis proposal at least one semester prior to the thesis defense. The student's faculty advisor assumes the primary responsibility for monitoring the program and directing the thesis work. The award of the thesis-based master's degree is contingent upon the student's researching and writing a thesis acceptable to the student's faculty advisor and thesis committee.

## 3. Thesis Defense

The student submits an initial draft of their thesis to the faculty advisor, who will work with the student on necessary revisions. Upon approval of the student's advisor, the revised thesis is circulated to the thesis committee members at least one week prior to the oral defense of the thesis. The oral defense of the thesis is scheduled during the student's final semester of study. Students must be registered in that semester to be able to defend their thesis. This defense session, which may include an examination of material covered in the student's coursework, will be open to the public.

Following the defense, the thesis committee will meet privately to vote on whether the student has successfully defended the thesis. Three outcomes are possible: the student may pass the oral defense; the student may fail the defense; or the committee may vote to adjourn the defense to allow the student more time to address and remove weaknesses or inadequacies in the thesis or underlying research.

Two negative votes will constitute a failure regardless of the number of committee members present at the thesis defense. In the event of either failure or adjournment, the chair of the thesis committee will prepare a written statement indicating the reasons for this action and will distribute copies to the student, the thesis committee members, the student's department head or program director, and the graduate dean. In the case of failure or adjournment, the student may request a re-examination, which must be scheduled no less than one week after the original defense. A second failure to defend the thesis satisfactorily will result in the termination of the student's graduate program.

Upon passing the oral defense of the thesis, the student must make any corrections in the thesis required by the thesis committee. The final, corrected copy and an executed signature page indicating approval by the student's advisor and department head must be submitted to the Office of Graduate Studies for review of the thesis format. (Instructions on Mines thesis format policy are available on the Office of Graduate Studies webpage and should be thoroughly read before beginning work on the thesis.) Any necessary revisions to the format of the thesis must be completed by the student and approved by the Office of Graduate Studies prior to the posted deadlines for completion of the student's graduate degree.

### 4. Time Limitations

A candidate for a thesis-based master's degree must complete all requirements for the degree within five years of the date of admission into the degree program. Time spent on approved leaves of absence is included in the five-year time limit. Candidates not meeting the time limitation will be notified and withdrawn from their degree programs.

Candidates may apply for a one-time extension of this time limitation. This application must be made in writing and approved by the candidate's advisor, thesis committee, department head or program director, and the graduate dean. The application must include specific timelines and milestones for degree completion. If an extension is approved, failure to meet any timeline or milestone will trigger immediate withdrawal from the degree program.

If the graduate dean denies an extension request, the candidate may appeal this decision to the provost. The appeal must be made in writing, must specifically state how the candidate believes the request submitted to the dean met the requirements of the policy, and must be received no later than 10 business days from the date of notification of the dean's denial of the original request.

If a candidate is withdrawn from a degree program through this process (either by denial of an extension request or failure to meet a timeline or milestone) and wishes to re-enter the degree program, that candidate must formally reapply for readmission. The program has full authority to determine if readmission is to be granted and, if granted, to fully re-evaluate the candidate's work to date and determine its applicability to the new degree program.

# Doctor of Philosophy

## A. Credits and Academic Requirements

The doctor of philosophy degree requires completion of a minimum of 72 credits beyond the bachelor's degree. At least 24 credits must be research credits earned under the supervision of a Mines faculty advisor and at least 18 credits of coursework must be applied to the degree program. For more information about specific requirements, please refer to the appropriate department/program section of this catalog.

The degree also requires completion of a satisfactory doctoral thesis and successful oral defense of this thesis. The doctoral thesis is expected to report on original research that results in a significant contribution of new knowledge and/or techniques. The student's faculty advisor and the doctoral thesis committee must approve the program of study and the topic for the thesis.

## B. Residency Requirements

Doctoral students must complete a residency requirement during the course of their graduate studies. The purpose of this requirement is as follows:

- require students to become engaged in extended and focused research activities under the direct supervision of Mines faculty.
- allow students to become immersed in the culture of an academic environment.
- allow students to engage in the professional activities associated with their research discipline.
- ensure students have access to the research tools and expertise needed for their chosen research activity.
- ensure the conduct of cutting-edge research with the expectation that this research will be completed in a timely fashion so that it is still relevant to the larger research community.
- provide Mines faculty with the ability to directly evaluate the research and academic credentials of a student and as such protect the integrity of the degree, the department/program, and the institution.
- ensure the research produced by students claiming a Mines degree is actually the product of Mines' intellectual environment.
- make it clear that the intellectual property developed while in the degree program is the property of Mines as defined in the Faculty Handbook.

The residency requirement may be met by completing two semesters of full-time registration at Mines. The semesters need not be consecutive. Students may request an exception to the full-time registration requirement from the graduate dean. Requests for exception must be in writing, must clearly address how the student's learning experience has met the goals of the residency requirement, as articulated above, and must be submitted by both the student and the student's thesis advisor and be approved by the student's department head/program director.

Students in online doctoral programs are exempt from this residency requirement.

## C. Transfer of Credits

Up to 24 credits of graduate-level coursework may be transferred from other institutions toward the PhD degree subject to the restriction that those courses must not have been used as credit toward a bachelor's degree, must not be prerequisites or deficiencies, must have a letter grade of C or better, and must be graduate-level credits. Requests for transfer credit must be approved by the faculty according to a process defined by the student's home department or program. Transfer credits are not included in calculating the student's grade-point average at Mines.

In lieu of transfer credit for individual courses defined above, students who enter the PhD program with a thesis-based master's degree from another institution may transfer up to 36 credits in recognition of the

coursework and research completed for that degree. The request must be approved by the faculty according to a process defined by the student's home department or program.

## D. Faculty Advisor Appointments

When admitted, each doctoral student is assigned a graduate faculty advisor by the department or program. Students who are assigned temporary advisors at admissions will work with their department or program to have a permanent advisor assigned. PhD students changing a temporary advisor to a permanent advisor or selecting a new advisor will need the new faculty advisor approved by the Office of Graduate Studies by the end of the second semester at Mines.

Advisors will advise students with respect to the student's thesis direction, research, and selection of courses. Advisors must be designated as a Mines graduate faculty member. Please refer to the Faculty Handbook for a definition of what constitutes Mines graduate faculty. Upon approval by the graduate dean, adjunct faculty, teaching faculty, visiting professors, emeritus professors, and off-campus representatives may be designated additional co-advisors.

The department head or program director of the degree program, and the graduate dean, must approve all faculty advisor appointments.

## E. Minor Programs

Students may choose a minor program or programs at the PhD level consisting of 12 course credits in the minor program. The student's faculty advisor and doctoral thesis committee, including an appropriate minor committee member as described below, approve the course selection and sequence in the selected minor program. Students may choose to complete multiple minor programs. Each program must consist of at least 12 credits approved by the faculty advisor and doctoral thesis committee, including the appropriate minor committee members. Less than half of the credits applied toward the minor degree program may be in the form of transfer credits. Transfer credits applied toward a minor are included as part of the overall transfer limitation applied to the degree as defined above.

## F. Doctoral Thesis Committees

*The appointment status of faculty who can serve as voting members of a doctoral thesis committee was pending final approval by the Board of Trustees as of the date of publication of this catalog. Check with the Office of Graduate Studies for an update to the membership information provided below and if a catalog addendum is available.*

The graduate dean will approve a doctoral thesis committee whose members have been recommended by the student, the student's faculty advisor, the student's department head and whose members meet the minimum requirements listed below. Students should have a thesis committee approved by the end of their second year of study. This committee must have a minimum of four voting members that fulfill the following criteria:

1. The committee must include an advisor who must be classified as a full member of the graduate faculty and must meet the qualifications defined above. If two advisors are appointed, advisor and co-advisor, both shall be voting members of the committee.
2. The committee must have at least two voting members knowledgeable in the technical areas of the thesis in addition to the advisor(s) and who are designated as either a full or associate member of the graduate faculty.
3. The fourth required member of the committee must be a full member of the graduate faculty. However, this fourth member may not be an advisor, co-advisor, or minor representative, and must be from outside the advisor's primary department and the program of the minor representative. This committee member acts as thesis committee chairperson.
4. If a thesis co-advisor is assigned, this individual, whether a member of the graduate faculty (associate or full) or an off-campus member, becomes a fifth required member of the committee. Co-advisors must be voting members of the committee.
5. If a minor field is designated, an additional committee member must be included who is an expert in that field. Minor representatives must be full members of the graduate faculty who are participating faculty in the minor program area. If multiple minor programs are pursued, each must have a committee representative as defined above.
6. Additional members from Mines or off-campus may serve, either with full voting status or in a non-voting capacity. Mines members with voting status must meet the same criteria as those of required committee members. If off-campus members are nominated for voting status, the committee request form must include a brief resume of their education and/or experience that demonstrates their competence to judge the quality and validity of the thesis. Such members also must agree to assume the same responsibilities expected of on-campus committee members including, but not limited to, attendance at committee meetings, review of thesis proposals and drafts, and participation in oral examinations and defense.

Shortly after its appointment, the doctoral thesis committee meets with the student to hear a presentation of the proposed course of study and thesis topic. The committee and student must agree on a satisfactory program. The student's faculty advisor then assumes the primary responsibility for monitoring the program, directing the thesis work, arranging qualifying examinations, and scheduling the thesis defense.

Upon completion of all prerequisite and core curriculum course requirements of their program, students must submit a Degree Audit form documenting satisfactory completion of the core curriculum requirements. Deficiency and/or prerequisite courses may not be listed on the Degree Audit form. The form must have the written approval of all members of the advisor and thesis committee, if appropriate.

## G. Admission to Candidacy

Full-time students must complete the following requirements within the first two calendar years after enrolling into the PhD program:

- have an approved thesis committee form on file.
- complete all prerequisite and core curriculum course requirements of their program.
- demonstrate adequate preparation for and satisfactory ability to conduct doctoral research.
- be admitted into full candidacy for the degree.

If students are admitted with deficiencies, the appropriate department heads or program directors will provide the students written lists of courses required to remove the deficiencies. These lists will be given to the students no later than one week after the start of classes of their first semester in order to allow them to add/drop courses as necessary. Completion of prerequisites and deficiencies will be monitored by the department.

Each program also defines the process for determining whether its students have demonstrated adequate preparation for, and have

satisfactory ability to do, high-quality, independent doctoral research in their specialties. These requirements and processes are described under the appropriate program headings in the section of this catalog on Graduate Degree Programs and Description of Courses.

To graduate, all PhD students must submit all required paperwork, apply to graduate, complete the graduation checkout course, complete the Survey of Earned Doctorate, and submit the signed Thesis Defense form by the posted deadlines. In addition, PhD students must upload a content-approved thesis and have the formatting approved by the posted checkout deadlines.

## H. Thesis Defense

The doctoral thesis must be based on original research of excellent quality in a suitable technical field, and it must exhibit satisfactory literary merit. In addition, the format of the thesis must comply with Mines policy according to the guidelines upheld by the Office of Graduate Studies. (Formatting requirements are listed on the Office of Graduate Studies webpage and students should thoroughly read these guidelines before beginning work on the thesis.)

The thesis topic must be submitted in the form of a written proposal to the student's faculty advisor and the committee. The committee must approve the proposal at least one year before the thesis defense.

The student's faculty advisor is responsible for supervising the student's research work and consulting with other doctoral thesis committee members on the progress of the work. The advisor must consult with the committee on any significant change in the nature of the work. The student will submit an initial draft of their thesis to the advisor, who will work with the student on necessary revisions. Upon approval of the student's advisor, the revised thesis is distributed to the other members of the committee at least one week prior to the oral defense of the thesis.

The student must pass an oral defense of their thesis during the final semester of studies. Students must be registered to defend. This oral defense may include an examination of material covered in the student's coursework. The defense will be open to the public.

Following the defense, the doctoral thesis committee will meet privately to vote on whether the student has successfully defended the thesis. Three outcomes are possible: the student may pass the oral defense; the student may fail the defense; or the committee may vote to adjourn the defense to allow the student more time to address and remove weaknesses or inadequacies in the thesis or underlying research. Two negative votes will constitute a failure regardless of the number of committee members present at the thesis defense. In the event of either failure or adjournment, the chair of the doctoral thesis committee will prepare a written statement indicating the reasons for this action and will distribute copies to the student, the thesis committee members, the student's department head, and the graduate dean. In the case of failure, the student may request a re-examination, which must be scheduled no sooner than one week after the original defense. A second failure to defend the thesis satisfactorily will result in the termination of the student's graduate program.

Upon passing the oral defense of thesis, the student must make any corrections in the thesis required by the doctoral thesis committee. The final, corrected copy and an executed signature page indicating approval by the student's advisor and department head must be submitted to the Office of Graduate Studies for review of the thesis format. (Instructions on Mines thesis format policy are available on the Office of Graduate Studies webpage and should be thoroughly read before beginning work on the thesis.) Any necessary revisions to the format of the thesis must be completed by the student and approved by the Office of Graduate Studies prior to the posted deadlines for completion of the student's graduate degree.

## I. Time Limitations

A candidate for a thesis-based doctoral degree must complete all requirements for the degree within nine years of the date of admission into the degree program. Time spent on approved leaves of absence is included in the nine-year time limit. Candidates not meeting the time limitation will be notified and withdrawn from their degree programs.

Candidates may apply for a one-time extension of this time limitation. This application must be made in writing and approved by the candidate's advisor, thesis committee, department head or program director, and the graduate dean. The application must include specific timelines and milestones for degree completion. If an extension is approved, failure to meet any timeline or milestone will trigger immediate withdrawal from the degree program.

If the graduate dean denies an extension request, the candidate may appeal this decision to the provost. The appeal must be made in writing, must specifically state how the candidate believes the request submitted to the dean met the requirements of the policy, and must be received no later than 10 business days from the date of notification of the dean's denial of the original request. The provost's decision is final.

If a candidate is withdrawn from a degree program through this process (either by denial of an extension request or failure to meet a timeline or milestone) and wishes to re-enter the degree program, that candidate must formally reapply for readmission. The program has full authority to determine if readmission is to be granted, and if granted, to fully re-evaluate the candidate's work to date and determine its applicability to the new degree program.

# Roles and Responsibilities of Committee Members and Students

Below are the roles and expectations Mines has of faculty as members of thesis committees and of students engaged in research-based degree programs.

## Thesis Advisor(s)

The thesis advisor has the overall responsibility for guiding the student through the process of the successful completion of a thesis that fulfills the expectations of scholarly work at the appropriate level as well as meets the requirements of the department or program and the school. The advisor shall:

- be able and willing to assume principal responsibility for advising the student.
- have adequate time for this work and be accessible to the student.
- provide adequate and timely feedback to both the student and the committee regarding student progress toward degree completion.
- guide and provide continuing feedback on the student's development of a research project by providing input on the intellectual appropriateness of the proposed activities, the reasonableness of project scope, acquisition of necessary resources and expertise, necessary laboratory or computer facilities, etc..

- establish key academic milestones and communicate these to the student and appropriately evaluate the student on meeting these milestones.

## Regular Committee Member

With the exception of the student's advisor, all voting members of the thesis committee are considered regular committee members. The regular committee member shall:

- have adequate time to assume the responsibilities associated with serving on a student's thesis committee.
- be accessible to the student (at a minimum this implies availability for committee meetings and availability to participate in a student's qualifying/comprehensive examinations – as dictated by the practices employed by the degree program – and the thesis defense).
- ensure that the student's work conforms to the highest standards of scholarly performance within the discipline and within the expertise provided by the committee member.
- provide advice to both the student and the student's advisor(s) on the quality, suitability and timeliness of the work being undertaken.
- approve the student's degree plan (e.g., courses of study, compliance with program's qualifying process, thesis proposal, etc.), assuring that the plan not only meets the intellectual needs of the student, but also all institutional and program requirements.
- review dissertation drafts as provided by the student and the advisor and provide feedback in a timely fashion.
- participate in and independently evaluate student performance in the final thesis defense.

## Minor Field Committee Representative

In addition to the responsibilities of a regular committee member, the minor field committee representative has the following added responsibilities:

- provide advice for and approval of coursework required as part of a student's minor degree program in a manner that is consistent with institutional and minor program requirements.
- as appropriate, participate in the student's qualifying and comprehensive examination process to certify completion of minor degree requirements.
- work individually with the student on the thesis aspects for which the minor committee member has expertise.

## Thesis Committee Chairperson

In addition to the responsibilities of a regular committee member, the chairperson of committee has the following added responsibilities:

- chair all meetings of the thesis committee including the thesis defense.
- represent the broad interests of the institution with respect to high standards of scholarly performance.
- represent the Office of Graduate Studies by ensuring that all procedures are carried out fairly and in accordance with institutional guidelines and policies.
- ensure that any potential conflicts of interest between student, advisor, or any other committee member are effectively identified and managed.

## Student Responsibilities

While it is expected that students receive guidance and support from their advisor and all members of the thesis committee, the student is responsible for actually defining and carrying out the program approved by the thesis committee and completing the thesis/dissertation. As such, it is expected that the student assumes a leadership role in defining and carrying out all aspects of their degree program and thesis/dissertation project. Within this context, students have the following responsibilities:

- to formally establish a thesis advisor and committee by the end of their first year of residence in their degree program.
- to call meetings of the thesis committee as needed.
- to actively inform and solicit feedback from their advisor and committee on progress made toward degree.
- to respond to, and act on feedback from their advisor and committee in a timely and constructive manner.
- to understand and comply with the terms of any contracts, fellowships, or agreements that may fund or guide their research.
- to understand and then apply the institutional and programmatic standards related to the ethical conduct of research in the completion of the thesis/dissertation.
- to know, understand and follow deadlines defined by the institution and the degree program related to all aspects of the degree program.

# Graduate Departments and Programs

Please choose from the list of links to access more information.


- Applied Mathematics and Statistics (p. 29)
- Chemical and Biological Engineering (p. 36)
- Civil and Environmental Engineering (p. 44)
- Chemistry (p. 58)
- Computer Science (p. 63)
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# Applied Mathematics and Statistics

## Degrees Offered

- Master of Science (Applied Mathematics and Statistics)
- Doctor of Philosophy (Applied Mathematics and Statistics)

## Program Description

The Department of Applied Mathematics and Statistics (AMS) at Colorado School of Mines prepares the next generation of mathematical and statistical scientists to be leaders in a world driven by increasingly complex technology and challenges. Our department is at the forefront of research in mathematical and statistical methods that are used to address the opportunities and challenges of the future. The AMS department offers two graduate degrees: A Master of Science in Applied Mathematics and Statistics and a Doctor of Philosophy in Applied Mathematics and Statistics. The master's program is designed to prepare candidates for careers in industry or government or for further study at the PhD level. The PhD program is sufficiently flexible to prepare candidates for careers in industry, government and academia. A course of study leading to the PhD degree can be designed either for students who have completed a master of science degree or for students with a bachelor of science degree.

The AMS department is also involved in the curriculum of three different interdisciplinary master's degree programs: Data Science, Operations Research with Engineering, and Quantitative Biosciences and Engineering. Please view Interdisciplinary Programs for more information on these programs.

Research within AMS is conducted in the following areas:

**Computational and Applied Mathematics**

- Deep Learning
- Differential and Integral Equations
- Dynamical Systems
- Geophysical and Environmental Applications
- High Performance Scientific Computing
- Mathematical Biology
- Meshfree Approximation Methods
- Multiscale Analysis and Simulation
- Numerical Methods for PDEs
- Optimal Control and Transport
- Wave Phenomena and Inverse Problems

**Statistics**

- Geophysical and Environmental Applications
- Methods for Massive Data Sets
- Spatial and Space-Time Processes
- Functional Data Analysis
- Inverse Problems
- Uncertainty Quantification

Master of Science Program Requirements

The master of science degree (non-thesis option) requires 30 credits of coursework. For both the Computational and Applied Mathematics and Statistics specialties, the curriculum structure consists of 1) a set of required courses, 2) a pair of MATH electives, and 3) general elective courses that serve to supplement the student's technical interests.

## *Specialty in Computational & Applied Mathematics*

*Required Courses*

| | | |
|---|---|---|
| MATH500 | LINEAR VECTOR SPACES | 3.0 |
| MATH501 | APPLIED ANALYSIS | 3.0 |
| MATH514 | APPLIED MATHEMATICS I | 3.0 |
| MATH550 | NUMERICAL SOLUTION OF PARTIAL DIFFERENTIAL EQUATIONS | 3.0 |
| MATH551 | COMPUTATIONAL LINEAR ALGEBRA | 3.0 |
| SYGN502 | INTRODUCTION TO RESEARCH ETHICS * | 1.0 |
| MATH589 | APPLIED MATHEMATICS AND STATISTICS TEACHING SEMINAR ** | 1.0 |

*Required only for students receiving federal support.
** Required only for students employed by the department as graduate teaching assistants or student instructor/lecturers.

Furthermore, students are required to complete two additional 500-level MATH courses.

Finally, the remaining 9 credits come from general elective courses and may be selected from any other graduate courses offered by the Department of Applied Mathematics and Statistics, except for specially designated service courses. Alternatively, up to 6 credits of elective courses may be taken in other departments on campus to satisfy this requirement.

## *Specialty in Statistics*

### *Required Courses*

| | | |
|---|---|---|
| MATH500 | LINEAR VECTOR SPACES | 3.0 |
| MATH531 | THEORY OF LINEAR MODELS | 3.0 |
| MATH534 | MATHEMATICAL STATISTICS I | 3.0 |
| MATH535 | MATHEMATICAL STATISTICS II | 3.0 |
| MATH560 | INTRODUCTION TO KEY STATISTICAL LEARNING METHODS I | 3.0 |
| MATH589 | APPLIED MATHEMATICS AND STATISTICS TEACHING SEMINAR ** | 1.0 |
| SYGN502 | INTRODUCTION TO RESEARCH ETHICS * | 1.0 |

*Required only for students receiving federal support.
** Required only for students employed by the department as graduate teaching assistants or student instructor/lecturers.

Furthermore, students are required to complete two additional 500-level MATH courses.

Finally, the remaining 9 credits come from general elective courses and may be selected from any other graduate courses offered by the Department of Applied Mathematics and Statistics, except for specially designated service courses. Alternatively, up to 6 credits of elective courses may be taken in other departments on campus to satisfy this requirement.

***The Master of Science degree (thesis option) requires 30 credits of acceptable coursework and research, completion of a satisfactory thesis, and successful oral defense of this thesis. A minimum of 6 (and a maximum of 12) of the 30 credits must be designated for supervised research, which will be in lieu of electives. The coursework includes the required core curriculum for the chosen specialty described above.***

## Mines Combined Undergraduate/Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

## Doctor of Philosophy Program Requirements

The Doctor of Philosophy requires 72 credits beyond the bachelor's degree. At least 24 of these hours must be thesis hours. Doctoral students must pass the comprehensive examination (a qualifying examination and thesis proposal), complete a satisfactory thesis, and successfully defend their thesis.

## *Specialty in Computational & Applied Mathematics*

### *Required Courses*

| | | |
|---|---|---|
| MATH500 | LINEAR VECTOR SPACES | 3.0 |
| MATH501 | APPLIED ANALYSIS | 3.0 |
| MATH514 | APPLIED MATHEMATICS I | 3.0 |
| MATH550 | NUMERICAL SOLUTION OF PARTIAL DIFFERENTIAL EQUATIONS | 3.0 |
| MATH551 | COMPUTATIONAL LINEAR ALGEBRA | 3.0 |
| SYGN502 | INTRODUCTION TO RESEARCH ETHICS * | 1.0 |
| MATH589 | APPLIED MATHEMATICS AND STATISTICS TEACHING SEMINAR ** | 1.0 |
| MATH588 | INTRODUCTION TO QUANTITATIVE AND COMPUTATIONAL RESEARCH | 1.0 |

*Required only for students receiving federal support.
** Required only for students employed by the department as graduate teaching assistants or student instructor/lecturers.

Furthermore, students are required to complete two additional 500-level MATH courses.

## *Specialty in Statistics*

### *Required Courses*

| | | |
|---|---|---|
| MATH500 | LINEAR VECTOR SPACES | 3.0 |
| MATH531 | THEORY OF LINEAR MODELS | 3.0 |
| MATH534 | MATHEMATICAL STATISTICS I | 3.0 |
| MATH535 | MATHEMATICAL STATISTICS II | 3.0 |
| MATH560 | INTRODUCTION TO KEY STATISTICAL LEARNING METHODS I | 3.0 |
| MATH588 | INTRODUCTION TO QUANTITATIVE AND COMPUTATIONAL RESEARCH | 1.0 |
| MATH589 | APPLIED MATHEMATICS AND STATISTICS TEACHING SEMINAR ** | 1.0 |
| SYGN502 | INTRODUCTION TO RESEARCH ETHICS * | 1.0 |

*Required only for students receiving federal support.
** Required only for students employed by the department as graduate teaching assistants or student instructor/lecturers.

Furthermore, students are required to complete two additional 500-level MATH courses.

**Further information can be found on the Web at ams.mines.edu. This website provides an overview of the programs, requirements, and policies of the department.**

## Fields of Research:

- Geophysical and Environmental Applications
- Scientific Data Compression
- Spatial and Space-Time Processes
- Methods for Massive Data Sets
- Functional Data Analysis
- Inverse Problems in Statistics
- Machine Learning
- Uncertainty Quantification
- Numerical Methods for PDEs
- High-Performance Scientific Computing
- Biological Fluid Dynamics
- Meshfree Approximation Methods
- PDEs and Kinetic Theory
- Computational Hydrology
- Mathematical Biology including:
  - Sleep and Circadian Rhythms
  - Blood Coagulation
  - Microorganism Motility
  - Epidemiology

## Courses

**MATH500. LINEAR VECTOR SPACES. 3.0 Semester Hrs.**
(I) Finite dimensional vector spaces and subspaces: dimension, dual bases, annihilators. Linear transformations, matrices, projections, change of basis, similarity. Determinants, eigenvalues, multiplicity. Jordan form. Inner products and inner product spaces with orthogonality and completeness. Prerequisite: MATH301, MATH332. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- to be completed at a later date

**MATH501. APPLIED ANALYSIS. 3.0 Semester Hrs.**
(II) Fundamental theory and tools of applied analysis. Students in this course will be introduced to Banach, Hilbert, and Sobolev spaces; bounded and unbounded operators defined on such infinite dimensional spaces; and associated properties. These concepts will be applied to understand the properties of differential and integral operators occurring

in mathematical models that govern various biological, physical and engineering processes. Prerequisites: MATH301 or equivalent.
**Course Learning Outcomes**

- 1) Show that a set or function is Lebesgue measurable. 2) Be able to describe Lp spaces and their properties. 3) Apply the Banach fixed point theorem. 4) Find the weak derivative of a function. 5) Solve problems involving metric spaces and their properties. 6) Solve problems involving fundamental definitions and theorems of Banach and Hilbert spaces.

**MATH503. FUNCTIONAL ANALYSIS. 3.0 Semester Hrs.**
(II) Properties of metric spaces, normed spaces and Banach spaces, inner product and Hilbert spaces. Fundamental theorems for normed and Banach spaces with applications. Orthogonality and orthonormal systems on Hilbert spaces with applications to approximation theory. Compact, bounded and unbounded operators. Duality, adjoint, self-adjoint, Hilbert-adjoint operators. Spectral analysis of linear operators. Applications to differential and integral equations. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- No change

**MATH506. COMPLEX ANALYSIS II. 3.0 Semester Hrs.**
(II) Analytic functions. Conformal mapping and applications. Analytic continuation.
Schlicht functions. Approximation theorems in the complex domain. Taught every other year. Prerequisite: MATH454. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- no change

**MATH510. ORDINARY DIFFERENTIAL EQUATIONS AND DYNAMICAL SYSTEMS. 3.0 Semester Hrs.**
(I) Topics to be covered: basic existence and uniqueness theory, systems of equations, stability, differential inequalities, Poincare-Bendixon theory, linearization. Other topics from: Hamiltonian systems, periodic and almost periodic systems, integral manifolds, Lyapunov functions, bifurcations, homoclinic points and chaos theory. Offered even years. 3 hours lecture; 3 semester hours. Prerequisite: MATH225 or MATH235 and MATH332 or MATH342 and MATH301.
**Course Learning Outcomes**

- no change

**MATH514. APPLIED MATHEMATICS I. 3.0 Semester Hrs.**
(II) The course focuses on the application of mathematical ideas and methods for solving problems in the applied sciences and engineering. Topics include dimensional analysis, regular and singular perturbation methods, boundary layer analysis, kinetics. Other topics may include variational calculus, boundary value problems and integral equations, and discrete models. Where applicable, there will be numerical approaches to complement the analytic ones.
**Course Learning Outcomes**

- No change

**MATH515. APPLIED MATHEMATICS II. 3.0 Semester Hrs.**
(II) The course focuses on the application of mathematical ideas and methods for solving problems in the applied sciences and engineering. Topics include non-numerical techniques for dealing with partial differential equations, wave phenomena, continuum mechanics, conservation laws, and transform methods.
**Course Learning Outcomes**

- no change

**MATH530. INTRODUCTION TO STATISTICAL METHODS. 3.0 Semester Hrs.**
(I,II) Review of probability, random variables, and discrete and continuous probability models. Descriptive statistics and graphical representations. General theory of Confidence intervals and hypothesis testing. Inferences for mean and variance of a single population. Inferences for means and variances for two populations. Inferences for proportions and count data. Prerequisites: MATH334.
**Course Learning Outcomes**

**MATH531. THEORY OF LINEAR MODELS. 3.0 Semester Hrs.**
(II) Statistical framework for estimation and inference based on multiple regression, including distribution theory for sums of squares statistics and estimators. Principles of analysis of variance (ANOVA), multiple comparisons, and experimental design. Also included are some relevant topics in multivariate analysis and asymptotic, large sample theory. Prerequisites. MATH332 and MATH534.

**MATH532. SPATIAL STATISTICS. 3.0 Semester Hrs.**
Modeling and analysis of data observed on a 2 or 3-dimensional surface. Random fields, variograms, covariances, stationarity, nonstationarity, kriging, simulation, Bayesian hierarchical models, spatial regression, SAR, CAR, QAR, and MA models, Geary/Moran indices, point processes, K-function, complete spatial randomness, homogeneous and inhomogeneous processes, marked point processes, spatio-temporal modeling. Course is offered every other year on even years. Prerequisites: MATH324 or equivalent.
**Course Learning Outcomes**

- no change

**MATH533. TIME SERIES ANALYSIS AND ITS APPLICATIONS. 3.0 Semester Hrs.**
Exploratory Analysis of Time Series, Stationary Time Series, Autocorrelation and Partial Autocorrelation, Autoregressive Moving Average (ARMA) Models, Forecasting, Estimation, ARIMA Models for Nonstationary Data, Multiplicative Seasonal ARIMA Models, The Spectral Density, Periodogram and Discrete Fourier Transform, Spectral Estimation, Multiple Series and Cross-Spectra, Linear Filters, Long Memory ARMA and Fractional Differencing, GARCH Models, Threshold Models, Regression with Autocorrelated Errors, Lagged Regression, Multivariate ARMAX Models. Prerequisites: MATH324, MATH335.
**Course Learning Outcomes**

- This course is designed to be useful for students facing the analysis of time-correlated data in the physical, biological, and social sciences.

**MATH534. MATHEMATICAL STATISTICS I. 3.0 Semester Hrs.**
(I) The basics of probability, discrete and continuous probability distributions, sampling distributions, order statistics, convergence in probability and in distribution, and basic limit theorems, including the central limit theorem, are covered. Prerequisite: none. 3 hours lecture; 3 semester hours.

**MATH535. MATHEMATICAL STATISTICS II. 3.0 Semester Hrs.**
(II) The basics of hypothesis testing using likelihood ratios, point and interval estimation, consistency, efficiency, sufficient statistics, and some nonparametric methods are presented. Prerequisite: MATH534 or equivalent. 3 hours lecture; 3 semester hours.

**MATH536. ADVANCED STATISTICAL MODELING. 3.0 Semester Hrs.**
(II) Modern extensions of the standard linear model for analyzing data. Topics include generalized linear models, generalized additive models, mixed effects models, and resampling methods. Offered every two years on odd years. 3 hours lecture; 3 semester hours. Prerequisite: MATH335, MATH324.
**Course Learning Outcomes**

- no change

**MATH537. MULTIVARIATE ANALYSIS. 3.0 Semester Hrs.**
(I) Introduction to applied multivariate representations of data for use in data analysis. Topics include introduction to multivariate distributions; methods for data reduction, such as principal components; hierarchical and model-based clustering methods; factor analysis; canonical correlation analysis; multidimensional scaling; and multivariate hypothesis testing.

**MATH538. STOCHASTIC MODELS. 3.0 Semester Hrs.**
(II) An introduction to the mathematical principles of stochastic processes. Discrete- and continuous-time Markov processes, Poisson processes, Brownian motion. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- no change

**MATH539. SURVIVAL ANALYSIS. 3.0 Semester Hrs.**
(I) Basic theory and practice of survival analysis. Topics include survival and hazard functions, censoring and truncation, parametric and non-parametric inference, the proportional hazards model, model diagnostics. Offered on odd years. Prerequisite: MATH335, MATH535. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- no change

**MATH540. PARALLEL SCIENTIFIC COMPUTING. 3.0 Semester Hrs.**
This course is designed to facilitate students' learning of high-performance computing concepts and techniques to efficiently perform large-scale mathematical modelling and data analysis using modern high-performance architectures (e.g. multi-core processors, multiple processors, and/or accelerators). Emphasis will be placed on analysis and implementation of various scientific computing algorithms in high-level languages using their interfaces for parallel or accelerated computing. Use of scripting to manage HPC workflows is included. Additional emphasis will be placed on design of parallel algorithms and implementation optimization in assignments. Prerequisites: MATH307 and CSCI200.
**Course Learning Outcomes**

- no change

**MATH547. SCIENTIFIC VISUALIZATION. 3.0 Semester Hrs.**
Equivalent with CSCI547,
Scientific visualization uses computer graphics to create visual images which aid in understanding of complex, often massive numerical representation of scientific concepts or results. The main focus of this course is on techniques applicable to spatial data such as scalar, vector and tensor fields. Topics include volume rendering, texture based methods for vector and tensor field visualization, and scalar and vector field topology. Students will learn about modern visualization techniques by reading and discussing research papers and implementing one of the algorithms described in the literature.

**MATH550. NUMERICAL SOLUTION OF PARTIAL DIFFERENTIAL EQUATIONS. 3.0 Semester Hrs.**
(I) Numerical methods for solving partial differential equations. Explicit and implicit finite difference methods; stability, convergence, and consistency. Alternating direction implicit (ADI) methods. Weighted residual and finite element methods. Prerequisites: MATH225 or MATH235 and MATH332 or MATH342.

**MATH551. COMPUTATIONAL LINEAR ALGEBRA. 3.0 Semester Hrs.**
(II) Numerical analysis of algorithms for solving linear systems of equations, least squares methods, the symmetric eigenproblem, singular value decomposition, conjugate gradient iteration. Modification of algorithms to fit the architecture. Error analysis, existing software packages. 3 hours lecture; 3 semester hours. Prerequisite: MATH332, MATH 307.

**MATH552. KERNEL-BASED APPROXIMATION METHODS. 3.0 Semester Hrs.**
Positive definite kernels play an important role in many different areas of mathematics, science and engineering. We put these kernels into perspective, both historically, as well as scientifically via connections to related fields such as analysis, approximation theory, the theory of integral equations, mathematical physics, probability theory and statistics, geostatistics, statistical or machine learning, and various kinds of engineering or physics applications. None of these fields is given a thorough theoretical treatment. Instead, these topics are presented via their relation to positive definite kernels. Prerequisite: Graduate level mathematical maturity and confidence to build on elements from (computational) linear algebra, functional analysis, and Gaussian processes, such as eigenvalues, eigenfunctions, orthogonality, change of basis, Sturm-Liouville theory, Green’s kernels, maximum likelihood estimation, Bayesian statistics, and convex optimization.
**Course Learning Outcomes**

- This course is designed to be useful for students interested in fitting multidimensional data (as arises, for example in many machine learning tasks) or numerically solving partial differential equations.

**MATH557. INTEGRAL EQUATIONS. 3.0 Semester Hrs.**
This is an introductory course on the theory and applications of integral equations. Abel, Fredholm and Volterra equations. Fredholm theory: small kernels, separable kernels, iteration, connections with linear algebra and Sturm-Liouville problems. Applications to boundary-value problems for Laplace's equation and other partial differential equations. Offered even years. Prerequisite: MATH332 or MATH342 and MATH455. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- no change

**MATH559. ASYMPTOTICS. 3.0 Semester Hrs.**
Equivalent with MATH459,
(I) Exact methods for solving mathematical problems are not always available: approximate methods must be developed. Often, problems involve small parameters, and this can be exploited so as to derive approximations: these are known as asymptotic approximations. Many techniques for constructing asymptotic approximations have been devised. The course develops such approximations for algebraic problems, the evaluation of integrals, and the solutions of differential equations. Emphasis is placed on effective methods and, where possible, rigorous analysis. Prerequisites: Calculus and ordinary differential equations. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- 1. Use asymptotic methods to solve algebraic problems
- 2. Use asymptotic methods to estimate integrals
- 3. Use asymptotic methods to solve differential equations.

**MATH560. INTRODUCTION TO KEY STATISTICAL LEARNING METHODS I. 3.0 Semester Hrs.**
Equivalent with DSCI560,
Part one of a two-course series introducing statistical learning methods with a focus on conceptual understanding and practical applications. Methods covered will include Introduction to Statistical Learning, Linear Regression, Cross validation, Basis Expansions, Regularization, Non linear Models, Model Assessment and Selection. Prerequisite: MATH335 or MATH530 or DSCI530.
**Course Learning Outcomes**

- Understand what statistical learning is, how it is done and how it relates to real-world problems.
- Understand the concepts, assumptions and applicability of linear regression and gain the practical skills to be able to apply regression analysis to real-world data.
- Understand the concepts, assumptions and applicability of classification and gain the practical skills to be able to apply classification analysis to real-world data.
- Understand what resampling methods are, how they work and in which situations they can be used. Apply resampling methods to real-world problems.
- Understand what basis expansions are, how they work and in which situations they can be applied. Address real-world problems with basis expansion solutions.
- Understand what regularization methods are, why they can be useful and how to apply them in the context of regression and classification problems.
- Gain knowledge of multiple ways to diagnose and assess statistical models and how to select among different models.

**MATH561. INTRODUCTION TO KEY STATISTICAL LEARNING METHODS II. 3.0 Semester Hrs.**
Part two of a two course series introducing statistical learning methods with a focus on conceptual understanding and practical applications. Methods covered will include Classification, Bootstrap, Tree-based Methods, Support Vector Machines, Unsupervised Learning. Prerequisite: MATH560 or DSCI560.
**Course Learning Outcomes**

- Gain knowledge of a variety of nonlinear modeling approaches including polynomial regression, regression splines, smoothing splines, local regression and generalized additive models. Understand when to apply these methods and gain practical knowledge doing so with real-world data.
- Gain knowledge of tree-based approaches, including regression and classification trees, bagging, random forests, and boosting. Be able to compare them to linear models and know when to apply them and do so with real-world data.
- Know what support vector machines are, when to apply them and how they compare to other classification methods. Test them with real-world data for two and more classes.
- Understand the conceptual basis of neural networks, for which types of problems they are useful and what potential drawbacks are. Build a neural network for real-world data.
- Gain an overview of unsupervised methods including Principal Components Analysis and different clustering methods. Apply these methods to solve real-world problems.

**MATH570. MATHEMATICAL MODELING OF SPATIAL PROCESSES IN BIOLOGY. 3.0 Semester Hrs.**
(II) This course is an introduction to mathematical modeling of spatial processes in biology. The emphasis is on partial differential equation models from a diverse set of biological topics such as cellular homeostasis, muscle dynamics, neural dynamics, calcium handling, epidemiology, and chemotaxis. We will survey a variety of models and analyze their results in the context of the biology. Mathematically, we will examine the diffusion equation, advection equation, and combinations of the two that include reactions. There will be a significant computational component to the course including bi-weekly computational labs; students will solve the model equations and perform computations using MATLAB.
**Course Learning Outcomes**

- 1. Describe classical spatial-temporal models in mathematical biology including diffusion-reaction, advection-reaction, and advection-diffusion-reaction
- 2. Derive partial differential equations models for spatial-temporal phenomena
- 3. Implement analytical and numerical techniques to solve and analyze spatial-temporal models
- 4. Assimilate current literature, extend it in a final project that advances the field, and communicate results professionally and effectively

**MATH572. MATHEMATICAL AND COMPUTATIONAL NEUROSCIENCE. 3.0 Semester Hrs.**
(II) This course will focus on mathematical and computational techniques applied to neuroscience. Topics will include nonlinear dynamics, hysteresis, the cable equation, and representative models such as Wilson-Cowan, Hodgkin-Huxley, and FitzHugh-Nagumo. Applications will be motivated by student interests. In addition to building basic skills in applied math, students will gain insight into how mathematical sciences can be used to model and solve problems in neuroscience; develop a variety of strategies (computational, theoretical, etc.) with which to approach novel mathematical situations; and hone skills for communicating mathematical ideas precisely and concisely in an interdisciplinary context. In addition, the strong computational component of this course will help students to develop computer programming skills and apply appropriate technological tools to solve mathematical problems. Prerequisite: MATH331. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Describe the classical models of mathematical neuroscience including Hodgkin-Huxley, Wilson-Cowan, and FitzHugh-Nagumo
- Implement analytical and numerical techniques to analyze models at different spatial and temporal scales
- Apply concepts from nonlinear dynamics including phase plane analysis, bifurcation theory, and model reduction techniques to analyze models in neuroscience
- Assimilate current literature, extend it in a final project that advances the field, and communicate results professionally and effectively

**MATH582. STATISTICS PRACTICUM. 3.0 Semester Hrs.**
(II) This is the capstone course in the Statistics Option. The main objective is to apply statistical knowledge and skills to a data analysis

problem, which will vary by semester. Students will gain experience in problem-solving; working in a team; presentation skills (both orally and written); and thinking independently. 3 hours lecture and discussion; 3 semester hours. Prerequisite: MATH 201 or 530 and MATH 324 or 531.

**MATH588. INTRODUCTION TO QUANTITATIVE AND COMPUTATIONAL RESEARCH. 1.0 Semester Hr.**
Students will be expected to use applied mathematics and statistics principles to critically analyze research results in published literature and place them in the context of related literature. Skills to be developed and discussed include critical review of the literature and oral defense of these reviews.
**Course Learning Outcomes**

- Critically analyze and evaluate research articles in applied mathematics and statistics
- Develop written syntheses that interpret, compare, and contrast multiple studies
- Effectively communicate these syntheses in the form of oral presentations
- Identify and describe effective communication styles in both research articles and oral presentations
- Identify knowledge gaps based on a synthesis of research articles and formulate new research questions/directions/applications

**MATH589. APPLIED MATHEMATICS AND STATISTICS TEACHING SEMINAR. 1.0 Semester Hr.**
(I) An introduction to teaching issues and techniques within the AMS department. Weekly, discussion-based seminars will cover practical issues such as lesson planning, grading, and test writing. Issues specific to the AMS core courses will be included. 1 hour lecture; 1.0 semester hour.

**MATH598. SPECIAL TOPICS. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**MATH598. SPECIAL TOPICS. 0-6 Semester Hr.**

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**MATH599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**MATH599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

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**MATH691. GRADUATE SEMINAR. 1.0 Semester Hr.**
(I) Presentation of latest research results by guest lecturers, staff, and advanced students. Prerequisite: none. 1 hour seminar; 1 semester hour. Repeatable for credit to a maximum of 12 hours.

**MATH692. GRADUATE SEMINAR. 1.0 Semester Hr.**
Equivalent with CSCI692,
(II) Presentation of latest research results by guest lecturers, staff, and advanced students. Prerequisite: none. 1 hour seminar; 1 semester hour. Repeatable for credit to a maximum of 12 hours.

**MATH693. WAVE PHENOMENA SEMINAR. 1.0 Semester Hr.**
(I, II) Students will probe a range of current methodologies and issues in seismic data processing, with emphasis on under lying assumptions, implications of these assumptions, and implications that would follow from use of alternative assumptions. Such analysis should provide seed topics for ongoing and subsequent research. Topic areas include: Statistics estimation and compensation, deconvolution, multiple suppression, suppression of other noises, wavelet estimation, imaging and inversion, extraction of stratigraphic and lithologic information, and correlation of surface and borehole seismic data with well log data. Prerequisite: none. 1 hour seminar; 1 semester hour.

**MATH698. SPECIAL TOPICS. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**MATH699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**MATH707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.**
(I, II, S) GRADUATE THESIS/DISSERTATION RESEARCH CREDIT Research credit hours required for completion of a Masters-level thesis or Doctoral dissertation. Research must be carried out under the direct supervision of the student's faculty advisor. Variable class and semester hours. Repeatable for credit.

## Department Head

G. Gustave Greivel, Teaching Professor

## Professors

Greg Fasshauer

Mahadevan Ganesh

Paul A. Martin

Doug Nychka

Stephen Pankavich

## Associate Professors

Soutir Bandopadhyay

Cecilia Diniz Behn

Dorit Hammerling

Luis Tenorio

## Assistant professors

Eileen Martin

Daniel McKenzie

Brennan Sprinkle

Samy Wu Fung

## Teaching Professors

Terry Bridgman

Debra Carney

Holly Eklund

Mike Mikucki

Mike Nicholas

Jennifer Strong

Scott Strong

Rebecca Swanson

## Teaching Associate Professor

Ashlyn Munson

## Teaching Assistant Professors

John Griesmer

Nathan Lenssen

Daisy Philtron

## Emeriti Professors

William R. Astle

Bernard Bialecki

Norman Bleistein

Ardel J. Boes

Austin R. Brown

John A. DeSanto

Graeme Fairweather

Raymond R. Gutzman

Frank G. Hagin

Willy Hereman

Donald C.B. Marsh

William Navidi

Steven Pruess

## Emeriti Associate Professors

Barbara B. Bath

Ruth Maurer

# Chemical and Biological Engineering

## Degrees Offered

- Master of Science (Chemical Engineering)
- Doctor of Philosophy (Chemical Engineering)
- Online Graduate Certificate in Chemical Engineering Processes in Energy Transitions

## Program Description

The Chemical and Biological Engineering Department of Colorado School of Mines is a dynamic, exciting environment for research and higher education. Mines provides a rigorous educational experience where faculty and top-notch students work together on meaningful research with far-reaching societal applications. Departmental research areas include bioengineering, catalysis, colloids and complex fluids, computational science, fuel cells, gas hydrates, membranes, polymers, and solar and electronic materials. Visit our webpage for additional information about our graduate program. https://chemeng.mines.edu/

## Program Requirements

## Prerequisites

The program outlined here assumes that the candidate for an advanced degree has a background in chemistry, mathematics, and physics equivalent to that required for the bachelor's degree in Chemical Engineering at Colorado School of Mines. Undergraduate course deficiencies must be removed prior to enrollment in graduate coursework.

The essential undergraduate courses include:

| | | |
|---|---|---|
| CBEN201 | MATERIAL AND ENERGY BALANCES | 3.0 |
| CBEN307 | FLUID MECHANICS | 3.0 |
| CBEN314 | CHEMICAL ENGINEERING HEAT AND MASS TRANSFER | 4.0 |
| CBEN357 | CHEMICAL ENGINEERING THERMODYNAMICS | 3.0 |
| CBEN375 | CHEMICAL ENGINEERING SEPARATIONS | 3.0 |
| CBEN418 | KINETICS AND REACTION ENGINEERING | 3.0 |
| **Total Semester Hrs** | | **19.0** |

# Required Curriculum

## Master of Science Program

## Master of Science (with Thesis)

Students entering the master of science (with thesis) program with an acceptable undergraduate degree in chemical engineering are required to take a minimum of 18 credits of coursework. All students must complete:

| Chemical Engineering core graduate courses | | |
|---|---|---|
| CBEN507 | APPLIED MATHEMATICS IN CHEMICAL ENGINEERING | 3.0 |
| or CBEN505 | NUMERICAL METHODS IN CHEMICAL ENGINEERING | |
| CBEN509 | ADVANCED CHEMICAL ENGINEERING THERMODYNAMICS | 3.0 |
| CBEN516 | ADVANCED TRANSPORT PHENOMENA | 3.0 |
| or CBEN530 | TRANSPORT PHENOMENA | |
| CBEN518 | REACTION KINETICS AND CATALYSIS | 3.0 |
| or CBEN519 | ADVANCED TOPICS IN HETEROGENEOUS CATALYSIS | |
| CBEN568 | INTRODUCTION TO CHEMICAL ENGINEERING RESEARCH AND TEACHING | 3.0 |
| CBEN707 | GRADUATE THESIS / DISSERTATION RESEARCH CREDIT | 6.0 |
| ELECT | Approved Coursework Electives | 6.0 |
| RESEARCH | Research Credits or Coursework | 3.0 |
| **Total Semester Hrs** | | **30.0** |

Students must take a minimum of 6 research credits, complete, and defend an acceptable master's dissertation. Between coursework and research credits a student must earn a minimum of 30 total credits. Full-time master's students must enroll in graduate colloquium (CBEN605) each semester. A maximum of 3 credits of CBEN605 can be counted towards the degree requirements.

## Master of Science (Non-Thesis)

Students entering the master of science (non-thesis) program with an acceptable undergraduate degree in chemical engineering are required to take a minimum of 30 credits of coursework. All students must complete:

| Chemical Engineering core graduate courses | | |
|---|---|---|
| CBEN507 | APPLIED MATHEMATICS IN CHEMICAL ENGINEERING | 3.0 |
| or CBEN505 | NUMERICAL METHODS IN CHEMICAL ENGINEERING | |
| CBEN509 | ADVANCED CHEMICAL ENGINEERING THERMODYNAMICS | 3.0 |
| CBEN516 | ADVANCED TRANSPORT PHENOMENA | 3.0 |
| or CBEN530 | TRANSPORT PHENOMENA | |
| CBEN518 | REACTION KINETICS AND CATALYSIS | 3.0 |
| or CBEN519 | ADVANCED TOPICS IN HETEROGENEOUS CATALYSIS | |
| ELECT | Approved Electives | 18.0 |
| **Total Semester Hrs** | | **30.0** |

Students may complete an acceptable engineering report for up to 6 credits. Full-time master's students must enroll in graduate colloquium (CBEN605) each semester. A maximum of 3 credits of CBEN605 can be counted toward the degree requirements.

## Mines Combined Undergraduate/graduate degree program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

## Doctor of Philosophy Program

The course of study for the PhD degree consists of a minimum of 30 credits of coursework. All PhD students must complete:

| Core courses | | |
|---|---|---|
| CBEN507 | APPLIED MATHEMATICS IN CHEMICAL ENGINEERING | 3.0 |
| CBEN509 | ADVANCED CHEMICAL ENGINEERING THERMODYNAMICS | 3.0 |
| CBEN516 | ADVANCED TRANSPORT PHENOMENA | 3.0 |
| CBEN518 | REACTION KINETICS AND CATALYSIS | 3.0 |
| CBEN568 | INTRODUCTION TO CHEMICAL ENGINEERING RESEARCH AND TEACHING | 3.0 |
| CBEN630 | PROPOSAL PREPARATION | 1.0 |
| CBEN | 600-Level Coursework Electives | 3.0 |
| ELECT | Approved Coursework Electives | 12.0 |
| CBEN707 | Graduate Research Credit (up to 12 hours per semester) | 42.0 |
| **Total Semester Hrs** | | **73.0** |

In addition, students must complete and defend an acceptable doctoral dissertation. Full-time PhD students must enroll in graduate colloquium (CBEN605) each semester. A maximum of 3 credits of CBEN605 can be counted toward the degree requirements.

Students in the PhD program are required to pass both a qualifying exam and the PhD proposal defense. After successful completion of 30 credits of coursework and completion of the PhD proposal defense, PhD candidates will be awarded a non-thesis master of science Degree. The additional requirements for the PhD program are described below.

## PhD Qualifying Examination

The PhD qualifying examination will be offered twice each year, at the start and end of the spring semester. All students who have entered the PhD program must take the qualifying examination at the first possible opportunity. However, a student must be in good academic standing (above 3.0 GPA) to take the qualifying exam.  A student may retake the examination once if he/she fails the first time; however, the examination must be retaken at the next regularly scheduled examination time. Failure of the PhD qualifying examination does not disqualify a student for the master's degree, although failure may affect the student's financial aid status.

The qualifying examination will cover the traditional areas of Chemical Engineering and will consist of two parts: GPA from core graduate

classes (CBEN507, CBEN509, CBEN516, and CBEN518) and an oral examination. The oral examination will consist of a presentation by the student on a technical paper from chemical engineering literature. Students will choose a paper from a list determined by the faculty. Papers for the oral examination will be distributed well in advance of the oral portion of the exam so students have sufficient time to prepare their presentations. The student is required to relate the paper to the core chemical engineering classes and present a research plan, followed by questions from the faculty. A one- to two-page paper on the research plan is due the Friday prior to the oral examination.

If a student fails the first attempt at the qualifying exam, his/her grade from a 600-level Chemical Engineering elective can replace the lowest grade from the core graduate classes for, and only for, the GPA calculation defined above.

## PhD Proposal Defense

After passing the qualifying exam, all PhD candidates are required to prepare a detailed written proposal on the subject of their PhD research topic. An oral examination consisting of a defense of the thesis proposal must be completed prior to their fifth semester. Written proposals must be submitted to the student's thesis committee no later than one week prior to the scheduled oral examination.

Two negative votes from the doctoral committee members are required for failure of the PhD proposal defense. In the case of failure, one re-examination will be allowed upon petition to the department head. Failure to complete the PhD proposal defense within the allotted time without an approved postponement will result in failure. Under extenuating circumstances, a student may postpone the exam with approval of the graduate affairs committee, based on the recommendation of the student's thesis committee. In such cases, a student must submit a written request for postponement that describes the circumstances and proposes a new date. Requests for postponement must be presented to the thesis committee no later than two weeks before the end of the semester in which the exam would normally have been taken.

# Online graduate certificate in Chemical engineering processes in energy transitions

The Mines graduate certificate in Chemical Engineering Processes in Energy Transitions is a three-course online program that provides engaging learning experiences in understanding current challenges and existing technologies in the safe production of energy, development of efficient energy storage systems, and associated environmental remediation methods related to carbon capture and utilization. Courses in the program focus on real-world challenges and state-of-the-art technologies. By bringing salient aspects of energy and environment under one umbrella, students develop the expertise necessary to address technological problems, make economic decisions, or formulate government policies. This program is designed for professionals and recent graduates who want to acquire new skills for career advancement or get a head start on an advanced graduate degree. The certificate program requires three 3-credit graduate courses identified below.

| | | |
|---|---|---|
| CBEN522 | CHEMICAL ENGINEERING FLOW ASSURANCE | 3.0 |
| CBEN598B | ADVANCED ELECTROCHEMICAL ENGINEERING | 3.0 |
| SYGN598A | NON-GEOLOGIC CCUS: CAPTURE & UTILIZATION | 3.0 |

## Courses

**CBEN504. ADVANCED PROCESS ENGINEERING ECONOMICS. 3.0 Semester Hrs.**
Advanced engineering economic principles applied to original and alternate investments. Analysis of chemical and petroleum processes relative to marketing and return on investments. Prerequisite: none. 3 hours lecture; 3 semester hours.

**CBEN505. NUMERICAL METHODS IN CHEMICAL ENGINEERING. 3.0 Semester Hrs.**
Engineering applications of numerical methods. Numerical integration, solution of algebraic equations, matrix 54 Colorado School of Mines Graduate Bulletin 2011 2012 algebra, ordinary differential equations, and special emphasis on partial differential equations. Emphasis on application of numerical methods to chemical engineering problems which cannot be solved by analytical methods. Prerequisite: none. 3 hours lecture; 3 semester hours.

**CBEN506. ADVANCED FUNCTIONAL POROUS MATERIALS. 3.0 Semester Hrs.**
Foundation on basic chemical strategies for making nanomaterials. Integration of fundamentals and functional applications of ordered porous materials at different length scales: from micro to macroporous regime. Chemical engineering concepts in nanochemistry. Existing and emerging functional applications of these porous materials in gas separations, heterogeneous catalysis, and adsorption.
**Course Learning Outcomes**

**CBEN507. APPLIED MATHEMATICS IN CHEMICAL ENGINEERING. 3.0 Semester Hrs.**
(I, II) This course stresses the application of mathematics to problems drawn from chemical and biological engineering fundamentals such as thermodynamics, transport phenomena, and kinetics. Formulation and solution of ordinary and partial differential equations arising in chemical engineering or related processes or operations are discussed. Prerequisite: Undergraduate differential equations course; undergraduate chemical engineering courses covering reaction kinetics, and heat, mass and momentum transfer. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- n/a

**CBEN508. NATURAL GAS PROCESSING. 3.0 Semester Hrs.**
Application of chemical engineering principles to the processing of natural gas. Emphasis on using thermodynamics and mass transfer operations to design and analyze the process for natural gas production, processing, and use. Relevant aspects of computer aided process simulation will be applied to facilitate the learning and understand the many components associated with natural gas as an energy resource.
**Course Learning Outcomes**

- 1. Demonstrate a basic understanding of the industry "from wellhead to burner tip"
- 2. Develop a basic understanding of gas chemistry and resulting physical properties
- 3. Develop an understanding of the processing steps needed to abide by transportation & usage requirements and specifications
- 4. Demonstrate the ability to use simulation software for natural gas characterization, fractionation, and related operations.

**CBEN509. ADVANCED CHEMICAL ENGINEERING THERMODYNAMICS. 3.0 Semester Hrs.**
Extension and amplification of under graduate chemical engineering thermodynamics. Topics will include the laws of thermodynamics, thermodynamic properties of pure fluids and fluid mixtures, phase equilibria, and chemical reaction equilibria. Prerequisite: CBEN357 or equivalent. 3 hours lecture; 3 semester hours.

**CBEN511. NEUROSCIENCE, MEMORY, AND LEARNING. 3.0 Semester Hrs.**
Equivalent with CBEN411,
(II) This course relates the hard sciences of the brain and neuroscience to memory encoding and current learning theories. Successful students in the course should be able to read, understand, and critique current, scholarly literature on the topic of Neuroscience, Memory, and Learning. When this course is cross-listed and concurrent with CBEN411, students that enroll in CBEN511 will complete additional and/or more complex assignments. Pre-requisites: CBEN110, CBEN120, CHGN221, CHGN222, PHGN100, and PHGN200. 3 hours lecture, 3 semester hours.

**Course Learning Outcomes**

- Define memory types and how they relate to different types of learning and list the biochemistry of memory generation, stabilization, and maintenance.
- State how brain systems relate to episodic and semantic memory and list neuroscience bases for actions, habits, and fear
- Generate and test hypotheses to improve learning, based on biochemistry

**CBEN513. SELECTED TOPICS IN CHEMICAL ENGINEERING. 1-3 Semester Hr.**
Selected topics chosen from special interests of instructor and students. Course may be repeated for credit on different topics. Prerequisite: none. 1 to 3 semester hours lecture/discussion; 1 to 3 semester hours.

**CBEN516. ADVANCED TRANSPORT PHENOMENA. 3.0 Semester Hrs.**
Principles of momentum, heat, and mass transport with applications to chemical and biological processes. Analytical methods for solving ordinary and partial differential equations in chemical engineering with an emphasis on scaling and approximation techniques. Convective transport in the context of boundary layer theory and development of heat and mass transfer coefficients. Introduction to computational methods for solving coupled transport problems in irregular geometries.
**Course Learning Outcomes**

- n/a

**CBEN518. REACTION KINETICS AND CATALYSIS. 3.0 Semester Hrs.**
(I) This course applies the fundamentals of kinetics, transport and thermodynamics to the analysis of gas-phase and catalytic reactions. A focus is placed on a molecular description of chemical kinetics with applications to the design and analysis chemical and biological reactors, complex reaction networks, and catalysis. Prerequisite: CBEN418 or equivalent. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- n/a

**CBEN519. ADVANCED TOPICS IN HETEROGENEOUS CATALYSIS. 3.0 Semester Hrs.**
Heterogenous catalysts are the workhorse of the chemical industry and are responsible for many of the critical chemical transformations tied to the technological progress of our society. From enabling the development of processes to produce gasoline for transportation and fertilizers for food security, passing through the development of car catalytic converters to eliminate toxic emissions, to now being called to play a central role in many technological challenges such as transforming CO2 to useful compounds, biomass to useful fuels, water to hydrogen fuels, powering cars using fuel cells, among many others. This grad/undergrad course will take the student on a learning journey through the state-of-the-art of catalyst development. The journey will be made through the fundamental basics of both computational/theoretical and experimental/practical aspects of catalyst development, with Special Topic sessions discussing the most up to date examples of synergistic integration of these aspects in industry and research. Not only will the student gain an understanding of what kind of critical societal problems are tried to be solved by developing new catalysts, but also will gain an understanding of how that development is taking place and what entails.
**Course Learning Outcomes**

- 1. Demonstrate an understanding of the crystal structures of solids and the origin of catalyst functions.
- 2. Demonstrate an understanding of adsorptions and reactions on surfaces.
- 3. Be able to use density functional theory (DFT) methods to calculate adsorption and activation energies and to estimate rate parameters from DFT-derived energies.
- 4. Be able to construct microkinetic modeling using theory-derived rate parameters and to predict rates and selectivities at catalytic conditions.
- 5. Be able to interpret experimental kinetic rate data and compare them to theory-derived values.
- 6. Demonstrate an understanding of diffusion phenomena in porous materials and its consequences on rates and selectivities.
- 7. Be able to analyze experimental and theoretical data to characterize diffusion in porous materials and to determine their textural properties.
- 8. Be able to explain different synthesis techniques to prepare catalytic materials.
- 9. Demonstrate an understanding of appropriate research tools that can be applied to characterize catalytic materials.
- 10. Demonstrate an understanding of the key physical chemistry concepts of spectroscopic methods.
- 11. Demonstrate an understanding of the applications of spectroscopic methods to answer specific research questions.

**CBEN522. CHEMICAL ENGINEERING FLOW ASSURANCE. 3.0 Semester Hrs.**
Chemical Engineering Flow Assurance will include the principles of the application of thermodynamics and mesoscopic and microscopic tools that can be applied to the production of oil field fluids, including mitigation strategies for solids, including gas hydrates, waxes, and asphaltenes.
**Course Learning Outcomes**

- 1. Demonstrate an understanding of the chemistry and physical properties of oil field production fluids and solids.
- 2. Demonstrate an understanding of the thermodynamics of oil field fluids and solids, including gas hydrates, waxes, and asphaltenes phase equilibria.
- 3. Be able to apply phase equilibrium models to predict the phase equilibria behavior of complex fluids, as well as gas solubility in water/oil systems.

- 4. Be able to apply multiphase flow transport models to predict pressure drop and slurry viscosity in oil and gas flowlines.
- 5. Demonstrate an understanding of the macroscopic, mesoscopic, and microscopic tools that can be applied to study oil field processing methods, including the control of hydrates, waxes, asphaltenes, scale.
- 6. Demonstrate an understanding of the appropriate chemical treatments and compatibility of the treatment processes for flow assurance.
- 7. Demonstrate an understanding of the key physical chemistry concepts of flow assurance.
- 8. Demonstrate an understanding of the key concepts of industrial gas transportation and storage.

**CBEN524. COMPUTER-AIDED PROCESS SIMULATION. 3.0 Semester Hrs.**
Advanced concepts in computer-aided process simulation are covered. Topics include optimization, heat exchanger networks, data regression analysis, and separations systems. Use of industry-standard process simulation software (Aspen Plus) is stressed. 3 hours lecture; 3 semester hours. Prerequisite: none.

**CBEN528. ADVANCED REACTOR DESIGN. 3.0 Semester Hrs.**
The heart (or, perhaps more appropriately, the stomach) of any chemical manufacturing or refining process is the reactor, where chemical and physical transformations occur under precisely controlled conditions. For traditional industrial chemical processes, the design, optimization and operation of conventional chemical reactors are extremely well developed, drawing upon the principles of chemistry, physics, calculus and economics. However, new-age process concepts proposing to use “exotic” reactors and/or sustainable inputs (e.g., renewable carbon resources, electrons, photons, plasma) face a dearth of well documented reaction engineering principles & design practices that eclipses their rapid adoption. CBEN 428/528 course features a survey of conventional and emerging non-conventional reactors to prepare students for career paths in applied academic or industrial research & development environments. For each reactor type, we introduce the geometry, transport limitations, fluid contacting patterns and options for heat management. Building on these fundamentals, we assess strategies for each reactor’s scale-up, connecting first principles to practical laboratory and reactor simulation approaches to target the information required to deploy the technology. In all cases, we emphasize conceptual reactor design requirements instead of mechanical details. Class time generally features whiteboard lectures and collaborative case studies of real-world reaction engineering examples. Prerequisites: CBEN418 or equivalent (instructor may make special exemptions).
**Course Learning Outcomes**

- Categorize idealized reactor archetypes, their flow patterns, design equations, rate expression forms and non-ideal behaviors
- Identify heterogeneous catalyst limitations and their influence on observable chemical kinetics
- Understand and differentiate among chemical kinetics, transport phenomena, thermodynamics and fluid contacting patterns as four distinct controlling factors within chemical reactors
- Quantitatively apply chemical engineering principles, data analysis and mathematical models to identify and determine performance-controlling phenomena for ideal and non-ideal reactors
- Analyze the geometry, transport limitations, fluid contacting patterns, heat management options, and design and scale-up methodologies for over 16 conventional industrial and non-conventional (e.g., renewably powered) reactors
- Apply the reaction engineering methodologies of #2–5 to critically assess experimental data reported in research literature and patents
- Effectively and concisely communicate engineering assumptions, problem-solving methods, inquiries, findings and resources used

**CBEN530. TRANSPORT PHENOMENA. 3.0 Semester Hrs.**
This course covers theory and applications of momentum, energy, and mass transfer based on microscopic control volumes. Analytical and numerical solution methods are employed in this course. Students registered for the 500-level version of this course will complete an additional project using finite element analysis software and present an oral or written report. Prerequisite: MATH225 or equivalent.
**Course Learning Outcomes**

- 1. Write Newton’s law of viscosity, Fourier’s law of heat conduction, and Fick’s law of diffusion. Define flux, gradient, averages, and velocity averages (i.e., bulk quantities).
- 2. Derive microscopic shell balances for the conservation of mass, momentum, energy, and chemical species, including energy sources and chemical reaction. Describe the similarities between conservation equations for momentum, energy and chemical species.
- 3. Apply the generalized equations of change for mass, energy and momentum transport in rectangular, cylindrical and spherical coordinates to describe transport problems.
- 4. Derive boundary conditions for physical problems involving transport of momentum, energy or chemical species. Distinguish between processes that occur at the interface and those that occur within the bulk fluid or material.
- 5. Choose and justify simplifying assumptions to facilitate the solution of a problem describing a physical process. State restrictions that will apply to the solution due to simplifying assumptions.
- 6. Solve limited cases of mass, momentum or energy transport, including unsteady-state and two-dimensional problems that require solutions by ordinary differential equations, separation of variables, and similarity transforms.
- 7. Describe boundary layer development in flow past a flat plate for transport of momentum, and heat or chemical species.
- 8. Define mass average and molar average velocities.
- 9. Describe moving reference frames. Interrelate various forms of Fick’s law based on mass average velocity, molar average velocity and stationary reference frames.
- 10. Describe and use analogies between momentum, heat and mass transport to obtain values for friction factors, heat transfer coefficients and mass transfer coefficients.
- 11. Define common dimensionless groups arising in transport problems (Reynolds, Prandtl, Schmidt, Sherwood, and Nusselt numbers) and relate analogous groups.
- 12. Demonstrate the ability to simulate coupled momentum, heat, and mass transfer phenomena in a technologically relevant problem using a finite element analysis solver. Further, demonstrate the ability to analyze the data and present in a written or oral report.

**CBEN531. IMMUNOLOGY FOR SCIENTISTS AND ENGINEERS. 3.0 Semester Hrs.**
(II) This course introduces the basic concepts of immunology and their applications in engineering and science. We will discuss the molecular, biochemical and cellular aspects of the immune system including structure and function of the innate and acquired immune

systems. Building on this, we will discuss the immune response to infectious agents and the material science of introduced implants and materials such as heart valves, artificial joints, organ transplants and lenses. We will also discuss the role of the immune system in cancer, allergies, immune deficiencies, vaccination and other applications such as immunoassay and flow cytometry. Prerequisites: Biology BIOL110 or equivalent or graduate standing.

**CBEN532. TRANSPORT PHENOMENA IN BIOLOGICAL SYSTEMS. 3.0 Semester Hrs.**
The goal of this course is to develop and analyze models of biological transport and reaction processes. We will apply the principles of mass, momentum, and energy conservation to describe mechanisms of physiology and pathology. We will explore the applications of transport phenomena in the design of drug delivery systems, engineered tissues, and biomedical diagnostics with an emphasis on the barriers to molecular transport in cardiovascular disease and cancer.
**Course Learning Outcomes**

- 1. Explain the barriers of momentum and mass transfer at the organism, organ, and cellular length scales.
- 2. Explain and interpret the primary literature on biotransport phenomena.
- 3. Apply the conservation of momentum equation and constitutive relationships to biologically relevant flows on different length scales and in different media.
- 4. Apply the conservation of species equation and constitutive relationships to biologically relevant mass transfer phenomena on different length scales and in different media.
- 5. Predict the relative importance of different forces and rate processes (diffusion, convection, and reaction) using dimensional analysis.
- 6. Use the Generate Ideas Method to formulate models of physiologic and pathologic processes.
- 7. Use the Generate Ideas Method to design therapeutic and diagnostic strategies.

**CBEN535. INTERDISCIPLINARY MICROELECTRONICS PROCESSING LABORATORY. 0-3 Semester Hr.**
Equivalent with MLGN535,PHGN435,PHGN535,
Application of science and engineering principles to the design, fabrication, and testing of microelectronic devices. Emphasis on specific unit operations and the interrelation among processing steps. 1 hour lecture, 4 hours lab; 3 semester hours.

**CBEN550. MEMBRANE SEPARATION TECHNOLOGY. 3.0 Semester Hrs.**
This course is an introduction to the fabrication, characterization, and application of synthetic membranes for gas and liquid separations. Industrial membrane processes such as reverse osmosis, filtration, pervaporation, and gas separations will be covered as well as new applications from the research literature. The course will include lecture, experimental, and computational (molecular simulation) laboratory components. Prerequisites: CBEN375, CBEN430. 3 hours lecture; 3 semester hours.

**CBEN554. APPLIED BIOINFORMATICS. 3.0 Semester Hrs.**
(II) In this course we will discuss the concepts and tools of bioinformatics. The molecular biology of genomics and proteomics will be presented and the techniques for collecting, storing, retrieving and processing such data will be discussed. Topics include analyzing DNA, RNA and protein sequences, gene recognition, gene expression, protein structure prediction, modeling evolution, utilizing BLAST and other online tools for the exploration of genome, proteome and other available databases. In parallel, there will be an introduction to the PERL programming language. Practical applications to biological research and disease will be presented and students given opportunities to use the tools discussed. General Biology BIOL110 or Graduate standing.

**CBEN555. POLYMER AND COMPLEX FLUIDS COLLOQUIUM. 1.0 Semester Hr.**
Equivalent with CHGN555,MLGN555,
The Polymer and Complex Fluids Group at the Colorado School of Mines combines expertise in the areas of flow and field based transport, intelligent design and synthesis as well as nanomaterials and nanotechnology. A wide range of research tools employed by the group includes characterization using rheology, scattering, microscopy, microfluidics and separations, synthesis of novel macromolecules as well as theory and simulation involving molecular dynamics and Monte Carlo approaches. The course will provide a mechanism for collaboration between faculty and students in this research area by providing presentations on topics including the expertise of the group and unpublished, ongoing campus research. Prerequisites: none. 1 hour lecture; 1 semester hour. Repeatable for credit to a maximum of 3 hours.

**CBEN568. INTRODUCTION TO CHEMICAL ENGINEERING RESEARCH AND TEACHING. 3.0 Semester Hrs.**
(I) Students will be expected to apply chemical engineering principles to critically analyze theoretical and experimental research results in the chemical engineering literature, placing it in the context of the related literature, and interact effectively with students in classroom. Skills to be developed and discussed include oral presentations, technical writing, proposal writing, principles of hypothesis driven research, critical review of the literature, research ethics, research documentation (the laboratory notebook), research funding, types of research, pedagogical methods, and assessment tools. Prerequisites: graduate student in Chemical and Biological Engineering in good standing. 3 semester hours.
**Course Learning Outcomes**

- Students will be able to apply chemical engineering principles to critically analyze theoretical and experimental research results in the chemical engineering literature, placing it in the context of the related literature, and interact effectively with students in classroom

**CBEN569. FUEL CELL SCIENCE AND TECHNOLOGY. 3.0 Semester Hrs.**
Equivalent with MEGN569,MLGN569,MTGN569,
(I) Investigate fundamentals of fuel-cell operation and electrochemistry from a chemical-thermodynamics and materials- science perspective. Review types of fuel cells, fuel-processing requirements and approaches, and fuel-cell system integration. Examine current topics in fuel-cell science and technology. Fabricate and test operational fuel cells in the Colorado Fuel Cell Center. 3 credit hours.

**CBEN570. INTRODUCTION TO MICROFLUIDICS. 3.0 Semester Hrs.**
This course introduces the basic principles and applications of microfluidics systems. Concepts related to microscale fluid mechanics, transport, physics, and biology are presented. To gain familiarity with small-scale systems, students are provided with the opportunity to design, fabricate, and test a simple microfluidic device. Students will critically analyze the literature in this emerging field. Prerequisites: CBEN307 or equivalent. 3 hours lecture, 3 semester hours.

**CBEN580. NATURAL GAS HYDRATES. 3.0 Semester Hrs.**
The purpose of this class is to learn about clathrate hydrates, using two of the instructor's books, (1) Clathrate Hydrates of Natural Gases, Third Edition (2008) co authored by C.A.Koh, and (2) Hydrate Engineering, (2000). Using a basis of these books, and accompanying programs,

we have abundant resources to act as professionals who are always learning. 3 hours lecture; 3 semester hours.

**CBEN584. FUNDAMENTALS OF CATALYSIS. 3.0 Semester Hrs.**
The basic principles involved in the preparation, charac terization, testing and theory of heterogeneous and homo geneous catalysts are discussed. Topics include chemisorption, adsorption isotherms, diffusion, surface kinetics, promoters, poisons, catalyst theory and design, acid base catalysis and soluble transition metal complexes. Examples of important industrial applications are given. Prerequisite: none. 3 hours lecture; 3 semester hours.

**CBEN598. SPECIAL TOPICS. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**CBEN598. SPECIAL TOPICS. 0-6 Semester Hr.**

**CBEN598. SPECIAL TOPICS. 0-6 Semester Hr.**

**CBEN598. SPECIAL TOPICS. 0-6 Semester Hr.**

**CBEN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**CBEN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

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**CBEN604. TOPICAL RESEARCH SEMINARS. 1.0 Semester Hr.**
Lectures, reports, and discussions on current research in chemical engineering, usually related to the student’s thesis topic. Sections are operated independently and are directed toward different research topics. Course may be repeated for credit. Prerequisite: none. 1 hour lecture-discussion; 1 semester hour. Repeatable for credit to a maximum of 3 hours.

**CBEN605. COLLOQUIUM. 1.0 Semester Hr.**
Students will attend a series of lectures by speakers from industry, academia, and government. Primary emphasis will be on current research in chemical engineering and related disciplines, with secondary emphasis on ethical, philosophical, and career-related issues of importance to the chemical engineering profession. Prerequisite: Graduate status.

**CBEN608. ADVANCED TOPICS IN FLUID MECHANICS. 1-3 Semester Hr.**
Indepth analysis of selected topics in fluid mechanics with special emphasis on chemical engineering applications. Prerequisite: CBEN508. 1 to 3 hours lecture discussion; 1 to 3 semester hours.

**CBEN609. ADVANCED TOPICS IN THERMODYNAMICS. 1-3 Semester Hr.**
Advanced study of thermodynamic theory and application of thermodynamic principles. Possible topics include stability, critical phenomena, chemical thermodynamics, thermodynamics of polymer solutions and thermodynamics of aqueous and ionic solutions. Prerequisite: none. 1 to 3 semester hours.

**CBEN610. APPLIED STATISTICAL THERMODYNAMICS. 3.0 Semester Hrs.**
Principles of relating behavior to microscopic properties. Topics include element of probability, ensemble theory, application to gases and solids, distribution theories of fluids, and transport properties. Prerequisite: none. 3 hours lecture; 3 semester hours.

**CBEN617. GRADUATE TRANSPORT PHENOMENA II. 3.0 Semester Hrs.**
(II) Analysis of momentum, heat, and mass transfer problems using advanced analytical and numerical methods with an emphasis on coupled transport problems and irregular geometries. Advanced analytical techniques may include regular and singular perturbation analysis, eigenvalue problems, finite Fourier transforms, and Laplace transforms. Numerical methods for solving differential equations include finite differences, finite elements, Monte Carlo methods, and computational fluid dynamics. Prerequisite: CBEN516. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Be able to solve transport problems analytically using regular and singular perturbation analysis, eigenvalue methods, finite Fourier transforms, and Laplace transforms.
- Be able to solve transport problems numerically using finite differences, finite elements, Monte Carlo methods, and commercial software

**CBEN620. ENGINEERING OF SOFT MATTER. 3.0 Semester Hrs.**
(II) Soft matter is a field of inquiry involving physical systems having low moduli and which are structured on length scales ranging from about 10 nanometers up to 100 microns. This graduate level class provides a survey of relevant material systems including polymers, colloids, surfactants, liquid crystals, and biological materials. The course emphasis is on the chemical physics of soft materials and therefore requires a high level of mathematical sophistication; students should have the equivalent of one semester of graduate level applied mathematics as a prerequisite. A term paper in the form of a short publishable review of a relevant topic is a major component of the class. Prerequisites: the equivalent of one semester of graduate level applied mathematics. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Be able to solve problems involving elastic materials including polymers, rubbers, and hydrogels through the calculation of molecular dimensions, moduli, swelling ratios, and other relevant quantities.
- Complete a publishable review article in on a topic in soft matter physics.
- Be capable of qualitatively describing different liquid crystalline phases and their technical applications. Perform calculations of free energies and other relevant thermodynamic quantities in order to predict the phase behavior of liquid crystals as a function of concentration, temperature, and pressure

**CBEN624. APPLIED STATISTICAL MECHANICS. 3.0 Semester Hrs.**
This course will introduce the both rigorous and approximate theories to estimate the macroscopic thermodynamic properties of systems based on laws that control the behavior of molecules. Course contents include classical dynamics and phase space, different types of ensembles, ideal and interacting gases, modern theory of liquids, ideal solids, as well

as molecular simulation techniques. Prerequisite: Undergraduate-level classical thermodynamics.
**Course Learning Outcomes**

- be able to calculate macroscopic theromodynamic properties based on both rigorous and approxiamte microscopic models

**CBEN625. MOLECULAR SIMULATION. 3.0 Semester Hrs.**
Principles and practice of modern computer simulation techniques used to understand solids, liquids, and gases. The quantum mechanical and statistical foundation of thermodynamics and kinetics will be discussed. In-depth discussion of Quantum Mechanics, Molecular Dynamics, and Monte Carlo simulation techniques will follow. Modern molecular interaction models, extended ensemble approaches, hybrid multiscale techniques, and mathematical algorithms used in molecular simulations will be included. Prerequisites: CBEN509, CBEN610.

**CBEN630. PROPOSAL PREPARATION. 1.0 Semester Hr.**
(I) This course is designed to guide students through the steps in writing a proposal. The Proposal writing process is divided into logical steps each of which when completed will lead to the graduate student having a draft proposal that could be successfully defended. Topics include: how to conduct a literature search and maintain an up to date database of relevant sources; Writing of a literature review in the context of a proposal; how to write a testable scientific hypothesis; the format and writing of a scientific paper; how best to present data and errors; an understanding of ethics and plagiarism issues; writing of a work plan with tasks related to objectives and time budget, Gantt charts; creation of a project budget; presentation techniques and oral defense of the proposal.

1 hour lecture; 1 semester. hour. Repeatable.
**Course Learning Outcomes**

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**CBEN670. ADVANCED MICROSCOPY FOR RESEARCH. 3.0 Semester Hrs.**
Microscopy is a widely used technique in research to study both biological systems and materials from nano- to macro-scales. The widespread use of microscopy is motivated by technologies that have minimized invasiveness of optical imaging, the variety of information that can be obtained, and the spatial and optical resolution afforded by new and emerging imaging technologies. This course will equip students and researchers with the knowledge to develop and apply advanced optical microscopy and imaging in their research. The course will cover the theoretical aspects which underlie optical imaging, including optical theory, fluorescence, and the interaction of light with matter. The course will then discuss the various technologies that are utilized in optical imaging, including microscopy, fluorophores including fluorescent proteins, optical biosensors, lasers, optical detectors, optical sectioning technology, and quantitative analysis of fluorescent images. The principle of operation of these technologies will be covered as well as assessing their strengths and weaknesses. Finally, the course will introduce a number of advanced optical imaging technologies and techniques which are increasingly being applied in biomedical research and will include hands on demonstrations of fluorescence microscopy.
**Course Learning Outcomes**

- Understand light and how microscopes utilize the properties of light.
- Understand microscope layout and use.
- Understand fluorescence and how fluorophores are used in research.
- Describe different types of advanced microscopy techniques, including common uses and limitations.
- Understand how to present microscopy images and quantitatively analyze the image data.
- Design and conduct experiments in biomedical research using microscopy and interpret the results.

**CBEN690. SUPERVISED TEACHING OF CHEMICAL ENGINEERING. 3.0 Semester Hrs.**
(I) Individual participation in teaching, outreach, and/or pedagogical research activities. Discussion, problem review and development, guidance of laboratory experiments, course development, supervised practice teaching. 6 to 10 hours supervised teaching; 3 semester hours. Prerequisite: Good academic standing, CBEN 507, CBEN 509, CBEN 516, CBEN 518.
**Course Learning Outcomes**

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**CBEN698. SPECIAL TOPICS IN CHEMICAL ENGINEERING. 3.0 Semester Hrs.**
Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles. Prerequisite: none.

**CBEN698. SPECIAL TOPICS. 0-6 Semester Hr.**

**CBEN698. SPECIAL TOPICS. 0-6 Semester Hr.**

**CBEN699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**CBEN699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**CBEN707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.**
(I, II, S) Research credit hours required for completion of a Masters-level thesis or Doctoral dissertation. Research must be carried out under the direct supervision of the student's faculty advisor. Variable class and semester hours. Repeatable for credit.

## Professors

Sumit Agarwal

Timothy A. Barbari

Anuj Chauhan

Andrew M. Herring

Carolyn A. Koh, William K. Coors Distinguished Chair of Chemical and Biological Engineering

David W.M. Marr, Gaylord & Phyllis Weaver Distinguished Professor, Chemical and Biological Engineering

Amadeu Sum

Colin A. Wolden

David T.W. Wu

### Associate Professors

Nanette Boyle, Interim Department Head

Kevin J. Cash

Diego A. Gómez-Gualdrón

Melissa D. Krebs

Joseph R. Samaniuk

Ning Wu

### Assistant Professors

Matthew Crane

Nikki Farnsworth

Ramya Kumar

Stephanie Kwon

Alexander Pak

### Teaching Professors

Jason C. Ganley

Tracy Q. Gardner

Rachel M. Morrish, Associate Department Head

Justin Shaffer

### Teaching Associate Professors

Michael D.M. Barankin

Cynthia L. Norrgran

C. Joshua Ramey

### Teaching Assistant Professor

Suzannah Beeler

### Professor of Practice

John L. Jechura

### Professors Emeriti

Robert M. Baldwin

Annette L. Bunge

Anthony M. Dean

James F. Ely, University Professor Emeritus

J. Thomas McKinnon

Ronald L. Miller

E. Dendy Sloan, Jr. , University Professor Emeritus

Charles Vestal

J. Douglas Way

Victor F. Yesavage

# Civil and Environmental Engineering

## Degrees Offered

- Master of Science in Civil and Environmental Engineering
- Doctor of Philosophy in Civil and Environmental Engineering
- Master of Science in Environmental Engineering Science
- Doctor of Philosophy in Environmental Engineering Science
- Graduate Certificate in Underground Construction and Tunnel Engineering
- Graduate Certificate in Environmental Modeling

## Program Description

The Civil and Environmental Engineering Department offers MS and PhD graduate degrees in Civil and Environmental Engineering (CEE) and Environmental Engineering Science (EES). Students entering this degree program should have a BS degree in engineering or science and will need to take or have taken all general and emphasis area-specific prerequisite courses.

Within the CEE degree, students complete specified requirements in one of three different emphasis areas: Environmental and Water Engineering, Geotechnical Engineering, and Structural Engineering.

The EES degree has a flexible curriculum that enables students with a BS degree in biology, chemistry, math, physics, geology, engineering, and other technical fields, to tailor a coursework program that best fits their career goals.

The non-thesis MS degrees in CEE and EES are eligible programs in the Western Regional Graduate Program (WRGP/WICHE), which promotes the sharing of higher education resources among participating western states. An important benefit of this designation is that students who are residents from Alaska, Arizona, California, Hawaii, Idaho, Montana, Nevada, New Mexico, North Dakota, Oregon, South Dakota, Utah, Washington, and Wyoming, as well as Commonwealth of the Northern Mariana Islands, Federal States of Micronesia, Guam, American Samoa, Republic of Palau, and Republic of the Marshall Islands may be eligible for discounted-rate non-resident tuition. More information on the WRGP program is available here.

The specific requirements for the EES and CEE degrees, as well as for the three emphasis areas within the CEE degree, are described in detail under the Major tab.

To achieve the MS degree, students may elect the non-thesis option, based exclusively upon coursework and project activities, or the thesis option, which requires coursework and research conducted under the guidance of a faculty advisor and MS thesis committee. The research is described in a final written thesis that is defended in an oral presentation.

The PhD degree requires students to complete a combination of coursework and original research, under the guidance of a faculty advisor and doctoral committee, that culminates in a significant scholarly contribution (e.g., in the form of published journal articles) to a specialized field in civil and environmental engineering or environmental engineering science. The written thesis must be defended in a public oral presentation

before the advisor and thesis committee. The PhD program may build upon one of the CEE or EES MS programs or a comparable MS program at another university. Full-time PhD enrollment is expected although part-time enrollment may be allowed under special circumstances.

## Civil and Environmental Engineering

**Geotechnical Engineering** is concerned with the engineering properties and behavior of natural and engineered geomaterials (soils and rocks), as well as the design and construction of foundations, earth dams and levees, retaining walls, embankments, and underground infrastructure including tunnels. Additionally, mitigation of the impact of natural hazards such as earthquakes and landslides, sustainable use of energy and resources, and reduction of the environmental impacts of human activities require geotechnical engineers who have in-depth understanding of how geomaterials respond to loads, and environmental changes.

**Structural Engineering** is a study area focused on natural and engineered structures and their behavior under environmental loading. Structural engineers use general principles of structural mechanics to conduct analyses of engineered materials and design structures for civil systems. Designed systems may include bridges, dams, buildings, tunnels, sustainable infrastructure, highways, biomechanical apparatus, sustainable civil engineering materials and numerous other structures and devices.

**Environmental and Water Engineering** is the application of environmental processes in natural and engineered systems. CEE faculty have expertise in water resource engineering, biosystems engineering, environmental chemistry, environmental microbiology, microbial genomics, wastewater treatment, water treatment, bioremediation, mining treatment processes and systems, remediation processes, biogeochemical reactions in soils, geobiology, membrane processes, humanitarian engineering, social aspects of engineering, and energy recovery from fluids.

## Environmental Engineering Science

**Environmental Engineering and Science** is the application of environmental processes in both natural and engineered systems. CEE faculty have expertise in water resource engineering, biosystems engineering, environmental chemistry, environmental microbiology, microbial genomics, wastewater treatment, water treatment, bioremediation, mining treatment processes and systems, remediation processes, biogeochemical reactions in soils, geobiology, membrane processes, humanitarian engineering, social aspects of engineering, and energy recovery from fluids. The EES degree does not require an undergraduate engineering degree; however, an undergraduate degree in science or engineering is preferable.

## Affiliated Interdisciplinary Degrees

**Humanitarian Engineering and Science (HES)** offers interdisciplinary programs of study targeted towards recent graduates or mid-career professionals with a BS in science and engineering who are interested in careers, research opportunities, and/or acquiring skills that will help them work effectively with communities. In both the master's degree and graduate certificates, a unique mix of social science, applied science, and engineering perspectives prepares students to apply knowledge about the earth to promote more sustainable and just uses of water, energy, and other earth resources and to understand and mitigate potential hazards.

For more information, see the HES section of this graduate catalog listed under Interdisciplinary Programs.

**Hydrologic Science and Engineering (HSE)** offers interdisciplinary programs of study in fundamental hydrologic science and applied hydrology with engineering applications. Our program encompasses groundwater hydrology, surface-water hydrology, vadose-zone hydrology, watershed hydrology, contaminant transport and fate, contaminant remediation, hydrogeophysics, and water policy/law. HSE is part of the Western Regional Graduate Program (WICHE), a recognition that designates the program as unique within the western United States. An important benefit of this designation is that students from several western states are given the tuition status of Colorado residents. These states include Alaska, Arizona, California, Hawaii, Idaho, Montana, Nevada, New Mexico, North Dakota, Oregon, South Dakota, Utah, Washington, and Wyoming.

The graduate degree program in HSE is offered jointly the Departments of Chemistry and Geochemistry, Civil and Environmental Engineering (CEE), Geology and Geological Engineering (GE), Geophysical Engineering, Humanities, Arts, and Social Sciences (HASS), Mechanical Engineering (ME), Mining Engineering (MN), and Petroleum Engineering (PE). Participating students reside in one of these departments, typically the home department of their advisor.

For more information, see the HSE section of this graduate catalog listed under Interdisciplinary Programs.

**Quantitative Biosciences and Engineering (QBE)** offers interdisciplinary programs of study in fundamental biosciences with engineering applications. Students may enroll in MS, non-thesis MS and PhD degree programs. As a foundation, our program encompasses core courses in cell biology and biochemistry, applied bioinformatics and systems biology with over 25 electives from biophysics to prosthetic and implant engineering to biomaterials to microfluids to geobiology. The graduate degree program in QBE is offered jointly by the Departments of Applied Mathematics and Statistics (AMS), Chemical and Biological Engineering (CBE), Chemistry and Geochemistry (CH), Civil and Environmental Engineering (CEE), Computer Science (CS), Geology and Geological Engineering (GE), Humanities, Arts, and Social Sciences (HASS), Mechanical Engineering (ME), and Physics (PH). Participating students reside in one of these departments, typically the home department of their advisor.

For more information, see the QBE section of this graduate catalog listed under Interdisciplinary Programs.

**Underground Construction and Tunnel Engineering** (UCTE) is an interdisciplinary field involving civil engineering, geological engineering and mining engineering, as well as mechanical engineering, geophysics, geology and others. UCTE deals with the design, construction, rehabilitation and management of underground space including caverns, shafts and tunnels for commercial, transportation, water and wastewater use. UCTE is a challenging field involving complex soil and rock behavior, groundwater conditions, excavation methods, construction materials, structural design flow, heterogeneity, and very low tolerance for deformation due to existing infrastructure in urban environments. Students pursuing a graduate degree or certificate in UCTE will gain a strong and interdisciplinary foundation in these topics. The graduate degree program in UCTE is offered jointly by the Departments of Civil and Environmental Engineering (CEE), Geology and Geological Engineering (GE), and Mining Engineering (MN). UCTE faculty from each department are collectively responsible for the operations of the program.

Participating students reside in one of these departments, typically the home department of their advisor.

For more information, see the UCTE section of this graduate catalog listed under Interdisciplinary Programs.

## Program Requirements

## General Degree Requirements for CEE and EES degrees:

MS Non-Thesis Option: 30 total credit hours (CH), consisting of coursework (27 CH) and either a three credit hour research based Independent Study (CEEN599) OR a designated design course (3 CH) and two semesters of seminar.

MS Thesis Option: 30 total credit hours (CH), consisting of coursework (24 CH), two semesters of seminar, and research (6 CH). Students must also write and orally defend a research thesis.

PhD: 72 total credit hours (CH), consisting of coursework (at least 24 CH), two semesters of seminar, and research (at least 24 CH). Students must also successfully complete qualifying examinations, prepare and present a thesis proposal, and write and defend a doctoral thesis. PhD students are also expected to submit the thesis work for publication in scholarly journals.

All students must take at least 18 credits within the CEEN prefix. The student may petition the advisor and/or thesis committee to allow reduction of the CEEN coursework requirement to a minimum of 15 credits (however, the core course requirements must be met).

## PhD Qualifying Exam

The student's graduate faculty advisor in conjunction with the graduate thesis committee administers the PhD qualifying exam. It is designed to test some of the attributes considered essential to successful doctoral level scholarship, including foundational knowledge, critical thinking, creativity, and communication skills. The student should take the exam within four semesters of enrollment in the PhD program unless the graduate thesis committee grants an extension.

The conduct of the qualifying exam is flexible, but typically involves both written and oral components. The written component might include several take-home questions set by members of the committee, and a review or research paper on a topic related to the student's intended research area. The duration of the written exam is set by the committee, but is expected to be approximately one week. As soon as practicable, following the return of the completed exam materials to the advisor, a meeting with the student and committee is scheduled, during which the student may be required to make an oral presentation of the paper review, followed by further oral examination of the other written materials and any other topics deemed appropriate by the committee. Following the oral component, the student is informed of the result of the examination (pass/fail), and the advisor informs the department head and graduate program manager of the outcome.

In the event the student does not pass the qualifying exam, the student may petition the department head for a re-examination within six months. If permission is granted, the dates of the re-examination are arranged in conjunction with the advisor and committee, and will follow the same guidelines as before.

A second failure of the qualifying exam does not disqualify a student for the MS degree but may affect the student's financial support status, and will result in a recommendation from the CEE department head to the graduate school that the student be dismissed from the CEE or EES PhD program.

## PhD Proposal Defense

The student's graduate faculty advisor, in conjunction with the graduate thesis committee, administers the PhD proposal defense. The purpose of the thesis proposal is to describe the student's research in sufficient detail to enable evaluation of its merit and viability. In general, the written proposal will describe the purpose and scope of work, anticipated results, literature review, preliminary findings, proposed research approach and methodologies, along with a schedule. No later than two weeks following submission of the thesis proposal to the committee, the student and committee will meet for an oral presentation, during which the student will be questioned about matters immediately relevant to the thesis proposal. The committee will reach a decision as to whether the proposed research is appropriate and achievable for a CEE or EES PhD degree. Following the meeting, the student is informed of whether the proposal has been approved, and the advisor informs the department head and department manager of the outcome.

In the event the student does not pass the proposal defense, he/she may petition the department head for a re-examination within six months. If permission is granted, the proposal can be revised for reconsideration by the committee, following exactly the same guidelines as before.

A second proposal defense failure will result in a recommendation from the CEE department head to the graduate school that the student be dismissed from the CEE or EES PhD program.

A PhD student must obtain approval of his/her thesis proposal by the committee at least one year before the final thesis defense.

NOTE: Affiliated Interdisciplinary Degree Programs may have a different PhD qualifying exam/proposal defense procedure.

## Mines' Combined Undergraduate / Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

## Civil and Environmental Engineering

## Prerequisites for CEE Degree:

- Baccalaureate degree: required, preferably in a science or engineering discipline
- College calculus I and II: two semesters required
- College physics: one semester required, two semesters highly recommended
- College chemistry I and II: two semesters required
- College statistics: one semester required
- Differential Equations
- **Emphasis Area Additional Requirements:**

- **Geotechnical and Structural –** Mechanics of Materials, Soil Mechanics, Structural Theory/Structural Analysis, Statics
- **Environmental and Water –** Fluid Mechanics

### Required Coursework for CEE Degrees:

CEE MS and PhD students must complete the coursework requirements for at least one emphasis area, comprised of core (required) courses and elective courses.

The student's advisor and committee (if MS thesis or PhD student) must approve elective courses.

Students must take at least 18 credits within the CEEN prefix. The student may petition the advisor and/or thesis committee to allow reduction of the CEEN coursework requirement to a minimum of 15 credits (however, the core course requirements must be met).

## Geotechnical Engineering

**Geotechnical Core Courses:** Students are required to successfully complete three courses from the following core course list plus CEEN590 Civil Engineering seminar (two semesters required).

| | | |
|---|---|---|
| CEEN506 | FINITE ELEMENT METHODS FOR ENGINEERS | 3.0 |
| CEEN510 | ADVANCED SOIL MECHANICS | 3.0 |
| CEEN511 | UNSATURATED SOIL MECHANICS | 3.0 |
| CEEN512 | SOIL BEHAVIOR | 3.0 |
| CEEN515 | HILLSLOPE HYDROLOGY AND STABILITY | 3.0 |
| CEEN519 | RISK ASSESSMENT IN GEOTECHNICAL ENGINEERING | 3.0 |
| CEEN523 | UNDERGROUND CONSTRUCTION ENGINEERING IN SOFT GROUND | 4.0 |
| CEEN582 | VADOSE ZONE HYDROLOGY | 3.0 |

## Structural Engineering

**Structural Engineering Core Courses:** Students are required to successfully complete three courses from the following core course list plus CEEN590 Civil Engineering seminar (two semesters required).

| | | |
|---|---|---|
| CEEN506 | FINITE ELEMENT METHODS FOR ENGINEERS | 3.0 |
| CEEN530 | ADVANCED STRUCTURAL ANALYSIS | 3.0 |
| CEEN531 | STRUCTURAL DYNAMICS | 3.0 |
| CEEN533 | MATRIX STRUCTURAL ANALYSIS | 3.0 |
| CEEN541 | DESIGN OF REINFORCED CONCRETE STRUCTURES II | 3.0 |
| CEEN542 | DESIGN OF WOOD STRUCTURES | 3.0 |
| CEEN543 | ADVANCED DESIGN OF STEEL STRUCTURES | 3.0 |
| CEEN545 | STEEL BRIDGE DESIGN | 3.0 |

## Environmental and Water Engineering

***Additional Prerequisites Courses:*** fluid mechanics.

**Environmental & Water Engineering Core Courses:** Students are required to successfully complete one course as specified in each of the following areas plus CEEN596 Environmental Seminar (two semesters required):

| | | |
|---|---|---|
| **Chemistry** | | |
| CEEN550 | PRINCIPLES OF ENVIRONMENTAL CHEMISTRY | 3.0 |
| **Physical Transport** | | |
| CEEN580 | CHEMICAL FATE AND TRANSPORT IN THE ENVIRONMENT | 3.0 |
| **Bio Processes** | | |
| CEEN566 | MICROBIAL PROCESSES, ANALYSIS AND MODELING | 3.0 |
| or CEEN560 | MOLECULAR MICROBIAL ECOLOGY AND THE ENVIRONMENT | |
| or CEEN562 | ENVIRONMENTAL GEOMICROBIOLOGY | |
| **Systems Design** | | |
| CEEN570 | WATER AND WASTEWATER TREATMENT | 3.0 |
| or CEEN578 | WATER TREATMENT DESIGN AND ANALYSIS | |
| **Seminar** | | |
| CEEN596 | ENVIRONMENTAL SCIENCE AND ENGINEERING SEMINAR | 0.0 |

## Designated Design Courses

| | | |
|---|---|---|
| **Geotechnical** | | |
| CEEN515 | HILLSLOPE HYDROLOGY AND STABILITY | 3.0 |
| CEEN523 | UNDERGROUND CONSTRUCTION ENGINEERING IN SOFT GROUND | 4.0 |
| **Structural** | | |
| CEEN541 | DESIGN OF REINFORCED CONCRETE STRUCTURES II | 3.0 |
| CEEN542 | DESIGN OF WOOD STRUCTURES | 3.0 |
| CEEN543 | ADVANCED DESIGN OF STEEL STRUCTURES | 3.0 |
| CEEN545 | STEEL BRIDGE DESIGN | 3.0 |
| CEEN547 | DESIGN OF PRESTRESSED CONCRETE STRUCTURES | 3.0 |
| CEEN549 | INTRODUCTION TO THE SEISMIC DESIGN OF STRUCTURES | 3.0 |
| **Environmental and Water** | | |
| CEEN570 | WATER AND WASTEWATER TREATMENT | 3.0 |
| CEEN575 | HAZARDOUS WASTE SITE REMEDIATION | 3.0 |
| CEEN578 | WATER TREATMENT DESIGN AND ANALYSIS | 3.0 |
| CEEN581 | WATERSHED SYSTEMS MODELING | 3.0 |
| CEEN584 | SUBSURFACE CONTAMINANT TRANSPORT | 3.0 |

## Environmental Engineering Science

## Prerequisites for EES degree:

- Baccalaureate degree: required, preferably in a science or engineering discipline
- College calculus I and II: two semesters required
- College physics: one semester required, two semesters highly recommended
- College chemistry I and II: two semesters required
- College statistics: one semester required

### Required Curriculum for Environmental Engineering Science (EES) Degree:

The EES curriculum consists of common core and elective courses that may be focused toward specialized areas of emphasis. The common core includes:

| | | |
|---|---|---|
| CEEN550 | PRINCIPLES OF ENVIRONMENTAL CHEMISTRY | 3.0 |
| CEEN580 | CHEMICAL FATE AND TRANSPORT IN THE ENVIRONMENT | 3.0 |
| CEEN566 | MICROBIAL PROCESSES, ANALYSIS AND MODELING | 3.0 |
| or CEEN560 | MOLECULAR MICROBIAL ECOLOGY AND THE ENVIRONMENT | |
| or CEEN562 | ENVIRONMENTAL GEOMICROBIOLOGY | |
| ENVIRONMENTAL BASED LAW OR POLICY COURSE [Commonly HASS Courses] | | 3.0 |
| CEEN596 | ENVIRONMENTAL SCIENCE AND ENGINEERING SEMINAR (two semesters required) | 0.0 |
| CEEN ELECT | 3.0 CR INDEPENDENT STUDY OR 3.0 cr DESIGN COURSE | 3.0 |

## Program Requirements

## Graduate Certificate in Underground Construction and Tunnel Engineering

The interdisciplinary Graduate Certificate in Underground Construction and Tunnel Engineering (UCTE) is comprised of the three signature courses listed below. The two anchor courses teach UCTE in hard rock and soft ground while the remaining course teaches underground infrastructure construction management principles.

Applicants for the certificate are required to be admitted into the combined BS + MS program or have an undergraduate degree in science or engineering, with geotechnical and mechanics of materials coursework, to be admitted into the certificate program. Students working toward the UCTE graduate certificate are required to successfully complete 10 credits, as detailed below. The courses taken for the graduate certificate can be used towards a master's or PhD degree at Mines.

| | | |
|---|---|---|
| CEEN523 | UNDERGROUND CONSTRUCTION ENGINEERING IN SOFT GROUND | 4.0 |
| CEEN532 | UNDERGROUND INFRASTRUCTURE CONSTRUCTION MANAGEMENT | 3.0 |
| or MNGN509 | CONSTRUCTION ENGINEERING AND MANAGEMENT | |
| MNGN504 | UNDERGROUND CONSTRUCTION ENGINEERING IN HARD ROCK | 3.0 |
| **Total Semester Hrs** | | **10.0** |

## Program Requirements

## Graduate Certificate in Environmental Modeling (9 credits)

The Environmental Modeling Graduate Certificate is an online or residential program focusing on the tools and methods for modeling environmental impacts of systems. Students will learn basic environmental modeling methods such as chemical fate and transport, risk assessment, and systems analysis. The certificate balances an introduction to environmental issues with a deep dive into environmental modeling. Students will gain perspective on the kinds of problems that can be solved with environmental modeling and will also acquire valuable modeling skills. Moreover, the coursework will cover a broad range of applications, making it relevant for varied scientific and engineering domains.

The 2 required courses in the certificate include:

| | | |
|---|---|---|
| CEEN580 | CHEMICAL FATE AND TRANSPORT IN THE ENVIRONMENT | 3.0 |
| CEEN501 | LIFE CYCLE ASSESSMENT | 3.0 |

To complete the certificate, students will select one elective from the following:

| | | |
|---|---|---|
| DSCI503 | ADVANCED DATA SCIENCE | 3.0 |
| GEGN575 | APPLICATIONS OF GEOGRAPHIC INFORMATION SYSTEMS | 3.0 |
| GEOL557 | EARTH RESOURCE DATA SCIENCE 1: FUNDAMENTALS | 3.0 |
| MNGN502 | GEOSPATIAL BIG DATA ANALYTICS | 3.0 |

**CEEN501. LIFE CYCLE ASSESSMENT. 3.0 Semester Hrs.**
(I, II) Which is more sustainable: paper vs plastic, hybrid vs electric vehicles? LCA is a powerful tool used to answer these questions; LCA quantifies the environmental sustainability of a product or process. Students will learn to conduct an LCA during a semester-long project of their choosing. At the end of the course students should be able to sit for the ACLCA professional LCACP certification exam. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- 1. Identify environmental sustainability challenges and opportunities for engineered systems from a life-cycle perspective
- 2. Draw a process flow diagram and Create a life cycle inventory
- 3. Understand and calculate different environmental impact categories
- 4. Conduct a simple life cycle assessment for a product or process
- 5. Utilize LCA results for decision making
- 6. Understand the process for conducting an ISO 14000 series certified LCA

**CEEN505. NUMERICAL METHODS FOR ENGINEERS. 3.0 Semester Hrs.**
(II) Introduction to the use of numerical methods in the solution of commonly encountered problems of engineering analysis. Structural/solid analysis of elastic materials (linear simultaneous equations); vibrations (roots of nonlinear equations, initial value problems); natural frequency and beam buckling (eigenvalue problems); interpretation of experimental data (curve fitting and differentiation); summation of pressure distributions (integration); beam deflections (boundary value problems). All course participants will receive source code of all the numerical methods programs published in the course textbook which is coauthored by the instructor. 3 hours lecture; 3 semester hours.

**CEEN506. FINITE ELEMENT METHODS FOR ENGINEERS. 3.0 Semester Hrs.**
(II) A course combining finite element theory with practical programming experience in which the multidisciplinary nature of the finite element method as a numerical technique for solving differential equations is emphasized. Topics covered include simple structural elements, beams on elastic foundations, solid elasticity, steady state analysis and transient analysis. Some of the applications will lie in the general area of geomechanics, reflecting the research interests of the instructor. Students get a copy of all the source code published in the course

textbook. 3 hours lecture; 3 semester hours. Prerequisite: Consent of the instructor.

**CEEN510. ADVANCED SOIL MECHANICS. 3.0 Semester Hrs.**
(I) Advanced soil mechanics theories and concepts as applied to analysis and design in geotechnical engineering. Topics covered will include seepage, consolidation, shear strength, failure criteria and constitutive models for soil. The course will have an emphasis on numerical solution techniques to geotechnical problems by finite elements and finite differences. 3 Lecture Hours, 3 semester hours. Fall even years. Prerequisite: A first course in soil mechanics.

**CEEN511. UNSATURATED SOIL MECHANICS. 3.0 Semester Hrs.**
(I) The focus of this course is on soil mechanics for unsaturated soils. It provides an introduction to thermodynamic potentials in partially saturated soils, chemical potentials of adsorbed water in partially saturated soils, phase properties and relations, stress state variables, measurements of soil water suction, unsaturated flow laws, measurement of unsaturated permeability, volume change theory, effective stress principle, and measurement of volume changes in partially saturated soils. The course is designed for seniors and graduate students in various branches of engineering and geology that are concerned with unsaturated soil's hydrologic and mechanics behavior. When this course is cross-listed and concurrent with CEEN412, students that enroll in CEEN511 will complete additional and/or more complex assignments. 3 hours lecture; 3 semester hours. Prerequisite: CEEN312.

**CEEN512. SOIL BEHAVIOR. 3.0 Semester Hrs.**
(I) The focus of this course is on interrelationships among the composition, fabric, and geotechnical and hydrologic properties of soils that consist partly or wholly of clay. The course will be divided into two parts. The first part provides an introduction to the composition and fabric of natural soils, their surface and pore-fluid chemistry, and the physico-chemical factors that govern soil behavior. The second part examines what is known about how these fundamental characteristics and factors affect geotechnical properties, including the hydrologic properties that govern the conduction of pore fluid and pore fluid constituents, and the geomechanical properties that govern volume change, shear deformation, and shear strength. The course is designed for graduate students in various branches of engineering and geology that are concerned with the engineering and hydrologic behavior of earth systems, including geotechnical engineering, geological engineering, environmental engineering, mining engineering, and petroleum engineering. When this course is cross-listed and concurrent with CEEN411, students that enroll in CEEN512 will complete additional and/or more complex assignments. 3 hours lecture; 3 semester hours.

**CEEN513. ADVANCED GEOMATERIAL MECHANICS. 4.0 Semester Hrs.**
This course deals with the classification and engineering behavior of soil and rock materials as well as materials used in underground construction such as structural steel, aggregates, cement, timber, concrete, shotcrete, accelerators and ground conditioning agents. This course presents an advanced treatment of soil and rock mechanics with focus on the following topics: Index and classification properties of soils, Physical properties and classification of intact rock and rock masses, Fluid flow in soils and rocks, Compressibility of soils and rocks, Failure theories and strength testing of soils and rocks, Shear strength of soils and rocks, Stresses and deformations around underground openings, Laboratory and field methods for evaluation of soil and rock properties, and Analytical and empirical approaches for the design and construction of structures in soil and rock materials. Undergraduate degree in a pertinent discipline of engineering or equivalent and undergraduate level knowledge of material behavior. 4 hours lecture; 4 semester hours.

**Course Learning Outcomes**

- Understand the behavior of coarse- and fine-grained soils in dry and saturated conditions
- Understand the stress-strain-strength behavior of soils in drained and undrained conditions
- Estimate the soil and rock shear strength properties for design purposes
- Evaluate the engineering properties of soils and rocks and determine appropriate input parameters for numerical models
- Evaluate the potential deformation of soil and rock and the stability of structure during staged construction
- Identify and explain significant considerations in choosing a material for a specific application including mechanical properties, durability, and sustainability.
- Follow standards to conduct tests of material properties and perform the calculations necessary to analyze and interpret test results.
- Work effectively in teams to perform experimental tasks and write formal technical report and convey engineering message efficiently.
- Use commercial engineering test equipment to determine mechanical properties of soil, rock, and construction materials
- Design and make conventional and high performance concrete and shotcrete mixtures and evaluate their fresh and hardened properties.

**CEEN515. HILLSLOPE HYDROLOGY AND STABILITY. 3.0 Semester Hrs.**
(I) Introduction of shallow landslide occurrence and socio-economic dynamics. Roles of unsaturated flow and stress in shallow landslides. Slope stability analysis based on unsaturated effective stress conceptualization. Computer modeling of unsaturated flow and stress distributions in hillslope. Prediction of precipitation induced shallow landslides. Prerequisite: CEEN312. 3 hours lecture; 3 semester hours.

**CEEN519. RISK ASSESSMENT IN GEOTECHNICAL ENGINEERING. 3.0 Semester Hrs.**
(I) Soil and rock are among the most variable of all engineering materials, and as such are highly amenable to a probabilistic treatment. Assessment of the probability of failure or inadequate performance is rapidly gaining ground on the traditional factor of safety approach as a more rational approach to design decision making and risk management. Probabilistic concepts are also closely related to system reliability and Load and Resistance Factor Design (LRFD). When probability is combined with consequences of failure, this leads to the concept of risk. This course is about the theory and application of various tools enabling risk assessment in engineering with an emphasis on geotechnical applications. Prerequisite: CEEN312. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Learn the basics of risk assessment in geotechnical engineering

**CEEN523. UNDERGROUND CONSTRUCTION ENGINEERING IN SOFT GROUND. 4.0 Semester Hrs.**
Design and construction of water, wastewater, transportation and utility tunnels, underground space and shafts/excavations in soft ground conditions (soil and weak rock). Addresses geotechnical site characterization, selection of design parameters, stability and deformation analysis of the ground and overlying structures, and construction methods. Includes design of temporary and permanent structural ground support according to ASD (allowable stress design) and LRFD (load resistance factor design) approaches, and design of ground improvement schemes and instrumentation/monitoring approaches to

mitigate risk. This course requires post-graduate level knowledge of soil mechanics, fundamental understanding of engineering geology, and an undergraduate level knowledge of structural analysis and design. Prerequisites: CEEN312. 4 semester hours.

**Course Learning Outcomes**

- 1. Understand the variety of underground construction methodologies, their application, strengths and limitations
- 2. Characterize, through analytical and numerical techniques, the 3d stress and deformation fields, and stability in various shaped shallow and deep underground openings (tunnels, caverns, shafts)
- 3. Analyze and design both temporary and permanent structural support/lining for underground openings (tunnels, caverns, shafts)
- 4. Understand and design ground improvement techniques
- 5. Analyze and design for groundwater control
- 6. Estimate deformation and damage to adjacent structures due to underground construction of tunnels, caverns, shafts
- 7. Implement a formal risk assessment and management process for underground construction
- 8. Identify appropriate geotechnical parameters and their uncertainties for analysis and design of underground spaces
- 9. In a team environment, analyze and design critical elements of a real-world underground construction project

**CEEN525. CEMENTITIOUS MATERIALS FOR CONSTRUCTION. 3.0 Semester Hrs.**

(II) Cementitious materials, as the most commonly used construction materials, are the main focus of this course and variety of cementitious materials including Portland and non-Portland cements, supplementary cementitious materials, concrete and sprayed concrete (shotcrete), and grouts with their needed additional constituents are covered in this course. This course provides a comprehensive treatment of engineering principles and considerations for proper design, production, placement and maintenance of high quality cementitious materials for infrastructure. In addition, cementitious materials and techniques used for ground improvement purposes are covered in this course. 3 semester hours.

**Course Learning Outcomes**

- 1. Describe the main properties of concrete constituents and their influence on the behavior • Describe the cement composition, phases, types, and the hydration process • List the different types of cements and their proper applications • Select the right types of admixtures to be used in different applications and situations • Describe the effects of supplementary cementitious materials on concrete properties
- 2. Design and Test Cementitious Construction materials to meet specifications • Design conventional and high performance Portland cement concrete mixtures with supplementary cementitious materials to meet specifications • Design concrete mix for spraying applications to meet the requirements for ground support needs • Identify the appropriate testing method for evaluation of concrete properties
- 3. Propose ground improvement solutions for different ground conditions using Cementitious Materials • Describe the different ground improvement techniques and explain the differences among current techniques • Identify the appropriate type of ground improvement and specify the requirements for the materials needed
- 4. Apply the concepts learned in the class in understanding the nature, types and applications of cementitious materials by • Selecting a topic of interest related to Cementitious Materials • Conducting research in groups • Presenting the work in written and oral presentation formats

**CEEN526. DURABILITY OF CONCRETE. 3.0 Semester Hrs.**

This course will provide an in-depth overview of concrete properties relevant to deterioration, including transport, mechanical, physical, and chemical properties. After this course, students should be able to identify, quantify, and mitigate against various deterioration mechanisms, such as freezing and thawing, sulfate attack, alkali-aggregate reactions, acid attack, and corrosion of steel rebar. This course will also illustrate how to test materials for durability (hands-on activities included) and ways in which construction methods may affect durability. Students will learn the strengths and limitations of the worlds most ubiquitous building material. 3 hours lecture; 3 semester hours.

**Course Learning Outcomes**

- 1. Explain how the microstructure of concrete develops.
- 2. Explain how the microstructure of concrete affects engineering properties.
- 3. Identify different deterioration mechanisms that affect concrete and explain how they impact concrete durability.
- 4. Explain the principles behind various durability tests.
- 5. Conduct durability tests and assess the performance.

**CEEN530. ADVANCED STRUCTURAL ANALYSIS. 3.0 Semester Hrs.**

(I) Introduction to advanced structural analysis concepts. Nonprismatic structures. Arches, Suspension and cable-stayed bridges. Structural optimization. Computer Methods. Structures with nonlinear materials. Internal force redistribution for statically indeterminate structures. Graduate credit requires additional homework and projects. Prerequisite: CEEN314. 3 hour lectures, 3 semester hours.

**CEEN531. STRUCTURAL DYNAMICS. 3.0 Semester Hrs.**

An introduction to the dynamics and earthquake engineering of structures is provided. Subjects include the analysis of linear and nonlinear single-degree and multi-degree of freedom structural dynamics. The link between structural dynamics and code-based analysis and designs of structures under earthquake loads is presented. The focus applications of the course include single story and multi-story buildings, and other types of structures that under major earthquake may respond in the inelastic range. Prerequisite: CEEN314. 3 hour lectures, 3 semester hours.

**CEEN532. UNDERGROUND INFRASTRUCTURE CONSTRUCTION MANAGEMENT. 3.0 Semester Hrs.**

In this course students will learn the fundamental and practical aspects of underground infrastructure construction management. Underground infrastructure includes tunnels for road, rail, transit, water, and utilities; shafts for tunnel access, ventilation, and pump stations; and excavations for underground transit stations, commercial, and recreational space, all of which comprises the civil infrastructure required for societies to grow and prosper. Through lectures, reading/viewing materials, case studies, assignments/exercises, and class discussions, as developed by current & former construction managers, students will gain practical instruction and practice on the traditional civil construction management process areas of contracts, procurement methods for public infrastructure, estimating and costs, scheduling, quality, safety, performance and risk management, and decision-making, all with a focus on underground infrastructure. Industry standards, specifications, and best practices that will be taught. Students will be exposed to what an underground infrastructure construction manager does on site: their roles & responsibilities, essential skillsets, and effective character attributes. Course topics also delve into the people management areas of communications, conflict resolution, stakeholder engagement, emotional intelligence, and leadership.

**CEEN533. MATRIX STRUCTURAL ANALYSIS. 3.0 Semester Hrs.**
Equivalent with CEEN433,
(II) Focused study on computer oriented methods for solving determinate and indeterminate structures such as trusses and frames. Classical stiffness based analysis method will be introduced with hands-on practice to develop customized matrix analysis program using Matlab. Commercial structural analysis programs will also be introduced during the class and practiced through class projects. When this course is cross-listed and concurrent with CEEN433, students that enroll in CEEN533 will complete additional and/or more complex assignments. 3 lecture hours, 3 semester hours. Prerequisite: CEEN314.
**Course Learning Outcomes**

- At the completion of this course, students will: 1. Gain fundamental understanding on Matrix analysis method and procedure, understand how commercial structural FEM packages work at a fundamental level 2. Be able to program basic linear member finite element code using Matlab 3. Use principle of virtual work to formulate matrix structural analysis elements 4. Use commercial structural analysis software to solve typical structural analysis problems 5. Gain fundamental Matlab programming and data process techniques # At the completion of CEEN533, students will be able to use Matlab to program matrix structural analysis code to solve determinate and indeterminate 3D truss and frame problems. This outcome will be measured by the completion of the programming tasks required in this class. Students' program will be evaluated and graded for correctness. # They will also be able to use a commercial structural analysis software package to construct 3D models for real structures, analyze the model under different static and dynamic loading conditions. This outcome will be measured by the completion of group project of modeling and analyzing a real structure using a commercial software program provide in the computer lab. # They will also be able to derive simple 2D line element stiffness matrix using the principle of virtual work. This outcome will be evaluated by a mid-term exam.

**CEEN540. CONCRETE BRIDGE DESIGN. 3.0 Semester Hrs.**
The course extends the coverage of steel design to include the topics: slender columns, beam-columns, frame behavior, bracing systems and connections, stability, moment resisting connections, composite design, bolted and welded connections under eccentric loads and tension, and semi-rigid connections. Course offered every third semester. 3 hours lecture; 3 semester hours.

**CEEN541. DESIGN OF REINFORCED CONCRETE STRUCTURES II. 3.0 Semester Hrs.**
Advanced problems in the analysis and design of concrete structures, design of slender columns; biaxial bending; two-way slabs; strut and tie models; lateral and vertical load analysis of multistory buildings; introduction to design for seismic forces; use of structural computer programs. Course offered every third semester. 3 hours lecture; 3 semester hours. Prerequisite: CEEN445.

**CEEN542. DESIGN OF WOOD STRUCTURES. 3.0 Semester Hrs.**
The course develops the theory and design methods required for the use of wood as a structural material. The design of walls, beams, columns, beam-columns, shear walls, and structural systems are covered with consideration of gravity, wind, snow, and seismic loads. Prerequisite: CEEN314 or equivalent.
**Course Learning Outcomes**

- Gain fundamental knowledge on engineered wood products, be able to recognize these products and find their design values in the code reference material
- Be able to navigate NDS code and SDPWS provisions
- Be able to design and check light frame wood structural components and simple systems
- Be able to design and check typical mass timber structural components and simple systems

**CEEN543. ADVANCED DESIGN OF STEEL STRUCTURES. 3.0 Semester Hrs.**
The course extends the coverage of steel design to include the topics: slender columns, beam-columns, frame behavior, bracing systems and connections, stability, moment resisting connections, composite design, bolted and welded connections under eccentric loads and tension, and semi-rigid connections. 3 hours lecture; 3 semester hours. Course offered every third semester. Prerequisite: CEEN443 or equivalent.

**CEEN544. STRUCTURAL PRESERVATION OF EXISTING AND HISTORIC BUILDINGS. 3.0 Semester Hrs.**
A broad discussion of historic structural systems in the United States, including stone and brick masonry, terra cotta, timber, cast and wrought iron, early steel, and early concrete. Combines research of historic manuals with contemporary analysis. Introduces nondestructive tests for historic structures. Enables prediction of deterioration mechanisms and structural deficiencies. Synthesizes structural retrofit solutions with preservation philosophy and current building codes. Emphasizes the engineer's role in stewardship of historic buildings. Every odd year Fall. 3 hours lecture and discussion; 3 semester hours. Prerequisite: CEEN443 and CEEN445.

**CEEN545. STEEL BRIDGE DESIGN. 3.0 Semester Hrs.**
Students are introduced to, and will develop an understanding of, the theory, analysis, and AASHTO code requirements for the design of steel bridge superstructures. The students will become familiar with bridge types, required loadings, composite action, plate girder design, and the Load and Resistance Factor Design method. The students will recognize the design requirements for a steel bridge superstructure and perform calculations for member loads and the loadings it transfers to the substructure. Course offered every third semester. Prerequisite: CEEN443.
**Course Learning Outcomes**

- Recognize requirements for steel bridge design
- Perform calculations to determine component loadings
- Analyze for effects of fatigue on welded bridge details
- Perform an approximate structural analysis of a multi-span steel bridge

**CEEN546. STATISTICAL METHODS FOR RELIABILITY AND ENGINEERING DESIGN. 3.0 Semester Hrs.**
(I, II) The course will introduce methods and principles that help quantifying the effects of uncertainty in the performance prediction of civil infrastructure systems. Students will learn to apply quantitative risk analysis and modeling approaches relevant to design problems in civil engineering. The course emphasizes that the systematic treatment of uncertainty and risk quantification are essential for adequate engineering planning, design, and operation of systems. The statistical approaches fundamental to engineering design and theory of reliability in structural and underground infrastructure design will be the focus of the course and examples. 3 hours lecture; 3 semester hours. Prerequisite: CEEN443.
**Course Learning Outcomes**

- Gain fundamental understanding on statistical and reliability methods and concepts.
- Be able to program basic statistical procedures using Matlab, and apply them to their research work including experimental data analysis and experiment design.
- Use first order second moment method and simulation method to estimate system reliability, understand how safety is ensured in design codes at a fundamental level.
- Gain basic understanding and simple application of performance based design

**CEEN547. DESIGN OF PRESTRESSED CONCRETE STRUCTURES. 3.0 Semester Hrs.**
Recognize the fundamental principles of prestressed concrete design and the behavior of prestressed members. Selecting the appropriate materials used to construct prestressed members. Perform the required calculations for the analysis and development of basic designs for prestressed beams, one-way slabs and bridge girders. Recognize the principles governing basic AASHTO prestressed concrete girder design. Read and interpret the applicable building code documents that govern prestressed concrete design. Course offered every third semester. Prerequisite: CEEN445.
**Course Learning Outcomes**

- 1. Recognize the fundamental principles of prestressed concrete design and the behavior of prestressed members.
- 2. Select the appropriate materials used to construct prestressed members.
- 3. Perform the required hand calculations for the analysis and development of basic designs for prestressed beams, one-way slabs and bridge girders.
- 4. Interpret the output of a common Post-Tension Concrete Design computer program.
- 5. Recognize the principles governing basic AASHTO prestressed concrete girder design.
- 6. Read and interpret the applicable building code documents that govern prestressed concrete design.

**CEEN548. STRUCTURAL LOADS. 3.0 Semester Hrs.**
Students will be introduced to the load types and load combinations required to design structures in compliance with building code requirements. Students will learn the theory and methods to determine the magnitude and application of loads associated with structure self-weight and occupancy. Students will be introduced to the physics underlying the requirements for environmental loads and to the accepted methods used to calculate environmental loads due to wind, snow, rain, floods, and avalanches. Students will become familiar with the common approaches used to deal with tsunami loads and blast loads. Students will learn the importance of and to recognize the load paths required to transmit applied loads from the structure to the foundation. Course offered every third semester. Prerequisite: CEEN314.
**Course Learning Outcomes**

- Students are expected to attend class, ask questions, utilize office hours when needed, and come to class prepared. Students are expected to display academic integrity (see Academic Integrity Section). Students will be able to determine to applicable loads to be used to design a structure, be able to calculate their magnitudes and directions, and specify load path.

**CEEN549. INTRODUCTION TO THE SEISMIC DESIGN OF STRUCTURES. 3.0 Semester Hrs.**
This course provides students with an introduction to seismic design as it relates to structures. Students will become familiar with the sources of seismic disturbances, the physics of seismic energy transmission, and the relationship between ground disturbance and the resulting forces experienced by structures. The theory and basis for existing building code provisions relating to seismic design of structures will be introduced. Building code requirements and design methodologies will be examined and applied. Advanced performance based seismic design method will also be introduced. Prerequisite: CEEN443, or CEEN445, or CEEN442 Co-requisite: None.
**Course Learning Outcomes**

- 1)
- 2)
- 3)
- 4)

**CEEN550. PRINCIPLES OF ENVIRONMENTAL CHEMISTRY. 0-3 Semester Hr.**
(I) This course provides an introduction to chemical equilibria in natural waters and engineered systems. Topics covered include chemical thermodynamics and kinetics, acid/base chemistry, open and closed carbonate systems, precipitation reactions, coordination chemistry, adsorption and redox reactions. 3 hours lecture; 3 semester hours. Prerequisite: none.

**CEEN551. ENVIRONMENTAL ORGANIC CHEMISTRY. 3.0 Semester Hrs.**
A study of the chemical and physical interactions which determine the fate, transport and interactions of organic chemicals in aquatic systems, with emphasis on chemical transformations of anthropogenic organic contaminants. Offered in alternate years. (Last offered Spring 23.) 3 semester hours.

**CEEN555. LIMNOLOGY. 3.0 Semester Hrs.**
(II) This course covers the natural chemistry, physics, and biology of lakes as well as some basic principles concerning contamination of such water bodies. Topics include heat budgets, water circulation and dispersal, sedimentation processes, organic compounds and their transformations, radionuclide limnochronology, redox reactions, metals and other major ions, the carbon dioxide system, oxygen, nutrients; planktonic, benthic and other communities, light in water and lake modeling. 3 hours lecture; 3 semester hours. Prerequisite: none.

**CEEN556. MINING AND THE ENVIRONMENT. 3.0 Semester Hrs.**
(I) The course will cover many of the environmental problems and solutions associated with each aspect of mining and ore dressing processes. Mining is a complicated process that differs according to the type of mineral sought. The mining process can be divided into four categories: Site Development; Extraction; Processing; Site Closure. Procedures for hard rock metals mining; coal mining; underground and surface mining; and in situ mining will be covered in relation to environmental impacts. Beneficiation, or purification of metals will be discussed, with cyanide and gold topics emphasized. Site closure will be focused on; stabilization of slopes; process area cleanup; and protection of surface and ground water. After discussions of the mining and beneficiation processes themselves, we will look at conventional and innovative measures to mitigate or reduce environmental impact.

**CEEN560. MOLECULAR MICROBIAL ECOLOGY AND THE ENVIRONMENT. 3.0 Semester Hrs.**
This course explores the diversity of microbiota in a few of the countless environments of our planet. Topics include microbial ecology (from a molecular perspective), microbial metabolism, pathogens, extreme environments, engineered systems, oxidation / reduction of metals, bioremediation of both organics and inorganics, microbial diversity, phylogenetics, analytical tools and bioinformatics. The course can have an integrated laboratory component (depends on timing) for applied molecular microbial ecology to learn microscopy, DNA extraction, PCR, gel electrophoresis, cloning, sequencing, data analysis and bioinformatic applications.

**CEEN562. ENVIRONMENTAL GEOMICROBIOLOGY. 3.0 Semester Hrs.**
(II) This course explores the functional activities and biological significance of microorganisms in geological and engineered systems with a focus on implications to water resources. Topics include: microorganisms as geochemical agents of change, mechanisms and thermodynamics of microbial respiration, applications of analytical, material science and molecular biology tools to the field, and the impact of microbes on the fate and transport of problematic water pollutants. Emphasis will be placed on critical analysis and communication of peer-reviewed literature on these topics. 3 hours lecture and discussion; 3 semester hours.

**CEEN564. ENVIRONMENTAL TOXICOLOGY. 3.0 Semester Hrs.**
This course provides an introduction to general concepts of ecology, biochemistry, and toxicology. The introductory material will provide a foundation for understanding why, and to what extent, a variety of products and by-products of advanced industrialized societies are toxic. Classes of substances to be examined include metals, coal, petroleum products, organic compounds, pesticides, radioactive materials, and others. Prerequisite: none. 3 hours lecture; 3 semester hours.

**CEEN566. MICROBIAL PROCESSES, ANALYSIS AND MODELING. 3.0 Semester Hrs.**
(II) Microorganisms facilitate the transformation of many organic and inorganic constituents. Tools for the quantitative analysis of microbial processes in natural and engineered systems will be presented. Stoichiometries, energetics, mass balances and kinetic descriptions of relevant microbial processes allow the development of models for specific microbial systems. Simple analytical models and complex models that require computational solutions will be presented. Systems analyzed include suspended growth and attached growth reactors for municipal and industrial wastewater treatment as well as in-stu bioremediation and bioenergy systems. 3 hours lecture; 3 semester hours.

**CEEN570. WATER AND WASTEWATER TREATMENT. 3.0 Semester Hrs.**
(I, II) Unit operations and processes in environmental engineering are discussed in this course, including physical, chemical, and biological treatment processes for water and wastewater. Treatment objectives, process theory, and practice are considered in detail. 3 hours lecture; 3 semester hours. Prerequisite: none.

**CEEN571. ADVANCED WATER TREATMENT ENGINEERING AND WATER REUSE. 3.0 Semester Hrs.**
This course presents issues relating to theory, design, and operation of advanced water and wastewater treatment unit processes and water reuse systems. Topics include granular activated carbon (GAC), advanced oxidation processes (O3/H2O2), UV disinfection, pressure-driven, current-driven, and osmotic-driven membranes (MF, UF, NF, RO, electrodialysis, and forward osmosis), and natural systems such as riverbank filtration (RBF) and soil-aquifer treatment (SAT). The course is augmented by CEEN571L offering hands-on experience using bench- and pilot-scale unit operations. 3 hours lecture; 3 semester hours. Prerequisite: CEEN470 or CEEN478 or CEEN570 or CEEN572.

**CEEN572. ENVIRONMENTAL ENGINEERING PILOT PLANT LABORATORY. 4.0 Semester Hrs.**
(II) This course provides an introduction to bench and pilot-scale experimental methods used in environmental engineering. Unit operations associated with water and wastewater treatment for real-world treatment problems are emphasized, including multi-media filtration, oxidation processes, membrane treatment, and disinfection processes. Investigations typically include: process assessment, design and completion of bench- and pilot-scale experiments, establishment of analytical methods for process control, data assessment, upscaling and cost estimation, and project report writing. Projects are conducted both at CSM and at the City of Golden Water Treatment Pilot Plant Laboratory. 6 hours laboratory; 4 semester hours. Prerequisite: CEEN550 and CEEN570.

**CEEN573. RECLAMATION OF DISTURBED LANDS. 3.0 Semester Hrs.**
Basic principles and practices in reclaiming disturbed lands are considered in this course, which includes an overview of present legal requirements for reclamation and basic elements of the reclamation planning process. Reclamation methods, including recontouring, erosion control, soil preparation, plant establishment, seed mixtures, nursery stock, and wildlife habitat rehabilitation, will be examined. Environmental policy, law and North America / global case studies also provide foundation to understand the field. Practitioners in the field will discuss their experiences.

**CEEN575. HAZARDOUS WASTE SITE REMEDIATION. 3.0 Semester Hrs.**
(I) This course covers remediation technologies for hazardous waste contaminated sites, including site characteristics and conceptual model development, remedial action screening processes, and technology principles and conceptual design. Institutional control, source isolation and containment, subsurface manipulation, and in situ and ex situ treatment processes will be covered, including unit operations, coupled processes, and complete systems. Case studies will be used and computerized tools for process selection and design will be employed. 3 hours lecture; 3 semester hours. Prerequisite: CEEN550 and CEEN580.

**CEEN578. WATER TREATMENT DESIGN AND ANALYSIS. 3.0 Semester Hrs.**
The learning objectives of this class are to build off of the information and theories presented in CEEN 470 and apply them to the design of water and wastewater treatment systems. Students will be presented with project-based assignments and, with the help of the instructors and associated lectures, will use fundamentals and commercial software to develop preliminary designs of water and wastewater systems. Students will gain experience in conventional and advanced treatment system design, software utilized by environmental consulting companies, and professional communication through the completion of this class. Course lectures will include fundamentals of design, guest lectures from practitioners, and tours of local treatment plants. Regional water and wastewater treatment employers (e.g., consultants, municipalities, industry, regulators) are actively searching for students with applied experience and this class will help promote the advancement of employment in the water and wastewater treatment field. Prerequisite: CEEN470.
**Course Learning Outcomes**

- At the completion of this course, students will: 1) Use fundamentals and commercial software to design and analyze water treatment

systems. 2) Integrate design aspects for development of integrated water systems to treat variable water resources. 3) Summarize design components into drawings and diagrams. 4) Communicate solutions and designs to practitioners through technical reports and presentations.

**CEEN580. CHEMICAL FATE AND TRANSPORT IN THE ENVIRONMENT. 3.0 Semester Hrs.**
(I, II) This course describes the environmental behavior of inorganic and organic chemicals in multimedia environments, including water, air, sediment and biota. Sources and characteristics of contaminants in the environment are discussed as broad categories, with some specific examples from various industries. Attention is focused on the persistence, reactivity, and partitioning behavior of contaminants in environmental media. Both steady and unsteady state multimedia environmental models are developed and applied to contaminated sites. The principles of contaminant transport in surface water, groundwater, and air are also introduced. The course provides students with the conceptual basis and mathematical tools for predicting the behavior of contaminants in the environment. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- No change

**CEEN581. WATERSHED SYSTEMS MODELING. 3.0 Semester Hrs.**
(II) Introduction to surface water modeling, including rainfall-runoff analysis, input data, uncertainty analysis, lumped and distributed modeling, parameter estimation and sensitivity analysis. Course is heavy on application of models across a range of diverse watersheds for streamflow and snowmelt predictions. In general, theoretical topics are covered in the first meeting each week, followed by hands-on application of concepts and models in the second meeting. Laptops and student Matlab licenses will be required for in-class activities. 3 hours lecture per week; 3 semester hours.

**CEEN582. VADOSE ZONE HYDROLOGY. 3.0 Semester Hrs.**
Introduction of soil chemical compositions and water properties. Introduction of soil classifi cation.Introduction of hydrological processes in vadose zone. Introduction of chemical potentialresponsible for soil water physical interactions: capillarity, cavitation, and adsorption. Introduction ofthermodynamic laws for multiphase, and multi-physics water movement and distribution in vadosezone. Introduction of concepts of soil water potential, matric potential, soil water retention curve, andhydraulic conduction function. Introduction of laws for capillary water fl ow, fi lm water fl ow, and vaporfl ow in soil. Introduction of governing equations for spatial-temporal distributions of soil moisture andmatric potential in vadose zone. Introduction of interactions between land surface and atmosphere,and between vadose zone and groundwater zone. Introduction of techniques for measuring soilwater retention curve and hydraulic conductivity function. Prerequisites: CEEN580 and knowledge of basic statistics and computer programming.
**Course Learning Outcomes**

- 1) Understand the Soil Water Potential concept to determine its components of the gravitational potential, capillary potential, and adsorptive potential
- 2) Understand techniques to measure Soil Water Retention Curve and Hydraulic Conductivity Function
- 3) Understand the laws governing fluid and vapor flows in vadose zone.
- 4) Understand the governing time-space equations for transient water flows in vadose zone.
- 5) Apply the fundamental principles to find the analytical and numerical solutions of multi-phase water distribution in vadose zone
- 6) Quantify and measure constitutive relations of Soil Water Retention Curve and Hydraulic Conductivity Function

**CEEN583. SURFACE WATER QUALITY MODELING. 3.0 Semester Hrs.**
This course will cover modeling of water flow and quality in rivers, lakes, and reservoirs. Topics will include introduction to common analytical and numerical methods used in modeling surface water flow, water quality, modeling of kinetics, discharge of waste water into surface systems, sedimentation, growth kinetics, dispersion, and biological changes in lakes and rivers. Prerequisites: CEEN480 or CEEN580 recommended. 3 hours lecture; 3 semester hours.

**CEEN584. SUBSURFACE CONTAMINANT TRANSPORT. 3.0 Semester Hrs.**
This course will investigate physical, chemical, and biological processes governing the transport and fate of contaminants in the saturated and unsaturated zones of the subsurface. Basic concepts in fluid flow, groundwater hydraulics, and transport will be introduced and studied. The theory and development of models to describe these phenomena, based on analytical and simple numerical methods, will also be discussed. Applications will include prediction of extents of contaminant migration and assessment and design of remediation schemes. Prerequisites: CEEN580. 3 hours lecture; 3 semester hours.

**CEEN585. FLUID MECHANICS FOR HYDROLOGY. 2.0 Semester Hrs.**
(I) This class focuses on the fundamental concepts of engineering fluid mechanics as they relate to the study of hydrology. Topics include fluid statics, dynamics, continuity, energy and momentum, dimensional analysis and open channel flow. Cross-listed with GEGN585. 2 semester hours.
**Course Learning Outcomes**

- 1. Students will solve problems on fundamental fluid mechanics concepts including hydrostatics, momentum, pressure and flow and energy systems.
- 2. Students will conduct simple dimensional analysis and explain its application to hydrologic research.
- 3. Students will solve problems related to flow measurement, fluid properties, and fluid statics.
- 4. Students will solve problems related to energy, impulse, and momentum equations.
- 5. Students will solve problems related to pipe and other internal flow.
- 6. Student will explain (or demonstrate or predict or describe or evaluate) how fluid mechanics relates to hydrological systems.

**CEEN585L. INTRODUCTION TO COMPUTATIONAL METHODS IN HYDROLOGY. 1.0 Semester Hr.**
This 1-cr class is a computational lab for the lecture course GEGN/CEEN 585 (Fluid Mechanics for Hydrology). The lab may be taken alone if a Fluid Mechanics lecture course has already been taken. The lab introduces the student to computational platforms and concepts germane to Fluid Mechanics and many other sciences. We use Matlab, Python, and various parallel programming environments to solve problems that use numerical integration, finite-difference solutions of first- and second-order ODEs, random walks to solve advection/diffusion problems, and various statistical concepts. Applications include calculating pressure on a submerged surface, bacterial growth/decay, laminar flow and solute transport between plates, and gradually-varying flow in open channels.

Prerequisites: Fluid Mechanics. Co-requisites: GEGN/CEEN 585 Fluid Mechanics for Hydrology.

**Course Learning Outcomes**

- • Design algorithms that can be implemented in modern programming environments including matlab, python, and fortran/openmp • Code useful programs for many different scientific applications, most notably surface water/groundwater hydrology. • Understand and apply concepts needed for parallel computing. • Present code that is readable and editable by others.

**CEEN586. HYDROMETEOROLOGY. 3.0 Semester Hrs.**

Hydrometeorology lies at the intersection of meteorology and hydrology, and covers key atmospheric processes relevant to flood prediction, droughts, heatwaves, streamflow, and energy transfer between the land surface and the atmosphere. In this course, you will be introduced to the conceptual foundations of hydrometeorology as they pertain to water prediction and water resource management. The course will cover weather and climate fundamentals, observational methods used in hydrometeorology, and data analysis methods relevant to decision-making and weather and water prediction.

**Course Learning Outcomes**

- 1)
- 2)
- 3)
- 4)

**CEEN587. HYDROCHEMICAL AND TRANSPORT PROCESSES. 3.0 Semester Hrs.**

(II) Analysis of the chemistry of natural waters in the context of hydrologic systems. The course focuses on sources and dynamic behavior of common natural and anthropogenically introduced solutes of interest, their interactions with minerals, and fate and transport in subsurface and surface environments. Students should NOT enroll in CEEN587 if they enroll(ed) in either CEEN580 or CEEN550. 3 hours lecture; 3 semester hours.

**Course Learning Outcomes**

- 1. Evaluate the chemistry of groundwater and surface water samples
- 2. Understand the sources and behavior of common solute of interest in natural systems
- 3. Apply chemical reaction kinetic equations to evaluate the dynamic behavior of common solutes of interest in natural systems
- 4. Evaluate fate and transport of contaminants in surface water and groundwater systems.

**CEEN589. WATER SUSTAINABILITY AND ENERGY PRODUCTION: CURRENT SCIENCE AND PRACTICE. 1.0 Semester Hr.**

This course is designed to provide students with valuable communication and professional skills while exploring in depth the topic of joint sustainability of water and unconventional petroleum energy production. A survey of current literature combined with key speakers will introduce the students to the field, while class sessions and practical exercises will help develop important communication, research, and interpersonal skills needed for future professionals. Course curriculum includes specific topics such as speaking/writing for a variety of audiences and critical thinking and analysis. This course is required for all ConocoPhillips - WE2ST Fellows, but is also open to any interested graduate students. 1 hour seminar; 1 semester hour.

**Course Learning Outcomes**

- Relevant Terminology and Current State of Hydraulic Fracturing
- Current State of Water Resources in CO in Relation to Users and Overall Water Budget
- Connections between Energy Development and Water Use
- Interpersonal Skill Development
- Technical Writing for a Variety of Audiences
- Technical Speaking for a Variety of Audiences
- Critical Analysis of Technical Issues
- Community Perceptions of Technical Topics

**CEEN590. CIVIL ENGINEERING SEMINAR. 1.0 Semester Hr.**

Required for all candidates for the M.S. and Ph.D. degrees in Chemistry. Full-time graduate students resident on campus must register for the course during each semester of their first four years of residency. Attendance at most departmental seminars is required, and all graduate students are required to present a departmental seminar. Prerequisites: Enrollment in Chemistry M.S. or Applied Chemistry Ph.D. degree program.

**CEEN591. EROSION CONTROL AND LAND RESTORATION. 3.0 Semester Hrs.**

Equivalent with ESGN571,

People have been the main cause of soil erosion for over 1,000 years. Studies suggest that human activities can cause about ten times more erosion than all natural processes together. It is well known that the rates of soil erosion surpass those of soil formation. Worldwide, millions of acres of productive land are lost every year because of inappropriate land management practices. The course is oriented to graduate and undergraduate students from any field in which the relationship among soil, water, and plant is altered, with the purpose of applying the right technique to bring back the productivity of land, in a sustainable way. The student will learn about erosion processes and how to stop them, and by the end of the course the student should be able to: (1) Identify erosive processes affecting certain area; (2) Evaluate the level of soil erosion, its origin and consequences to make further management decisions; and (3) Select and design the most appropriate erosion control/land restoration technique to apply, based on cost-effectiveness, giving emphasis to maximizing environmental benefits (i.e. using plants as a main stabilization system).

**Course Learning Outcomes**

**CEEN592. ENVIRONMENTAL LAW. 3.0 Semester Hrs.**

Equivalent with CEEN492,PEGN530,

This is a comprehensive introduction to U.S. Environmental Law, Policy, and Practice, especially designed for the professional engineer, scientist, planner, manager, consultant, government regulator, and citizen. It will prepare the student to deal with the complex system of laws, regulations, court rulings, policies, and programs governing the environment in the USA. Course coverage includes how our legal system works, sources of environmental law, the major USEPA enforcement programs, state/local matching programs, the National Environmental Policy Act (NEPA), air and water pollution (CAA, CWA), EPA risk assessment training, toxic/hazardous substances laws (RCRA, CERCLA, EPCRA, TSCA, LUST, etc.), and a brief introduction to international environmental law. Taught on Demand. 3 hours lecture; 3 semester hours.

**CEEN593. SUSTAINABLE ENGINEERING DESIGN. 3.0 Semester Hrs.**

Equivalent with ESGN593,

This course provides a comprehensive introduction to concepts of sustainability and sustainable development from an engineering point of view. Environmental and health impacts are quantitatively considered in engineering and design analysis through a Life Cycle Assessment (LCA)

tool. Social considerations, a key aspect of sustainable engineering design, are integrated throughout the design analysis. Prerequisite: Senior or graduate standing.

**Course Learning Outcomes**

- 1)
- 2)
- 3)
- 4)

**CEEN594. RISK ASSESSMENT. 3.0 Semester Hrs.**

This course evaluates the basic principles, methods, uses, and limitations of risk assessment in public and private sector decision making. Emphasis is on how risk assessments are made and how they are used in policy formation, including discussion of how risk assessments can be objectively and effectively communicated to decision makers and the public. Prerequisite: CEEN592 and one semester of statistics. 3 hours lecture; 3 semester hours.

**CEEN595. ANALYSIS OF ENVIRONMENTAL IMPACT. 3.0 Semester Hrs.**

Techniques for assessing the impact of mining and other anthropogenic activities on various components of the global ecosystem are considered. The National Environmental Policy Act of 1970 (NEPA) fundamentally changed how the environment is to be considered in any federal decision within the US and has become a model for nations worldwide. Training in the procedures of preparing Environmental Impact Statements (EIS) and Environmental Assessments (EA) are discussed with a particular emphasis on case studies of each, mostly focused on the western US, though all 50 states are considered. Course includes a review of pertinent laws and acts (i.e., NEPA, Endangered Species Act (ESA), Clean Water Act (CWA), Clean Air Act (CAA), Federal Land Policy Management Act (FLPMA), etc.) as well as organic acts that created the National Park Service (NPS), the US Forest Service (USFS) and the Bureau of Land Management (BLM) that deal with environmental impacts. Some field trips.

**CEEN596. ENVIRONMENTAL SCIENCE AND ENGINEERING SEMINAR. 0.0 Semester Hrs.**

Research presentations covering current research in a variety of environmental topics.. (Two semesters required.).

**CEEN597. PRACTICES AND PRINCIPLES OF ENVIRONMENTAL CONSULTING. 3.0 Semester Hrs.**

This course provides an in-depth understanding of the environmental consulting industry with a particular focus on problem solving and project delivery to meet expectations of professional services organizations (environmental consulting firms). Using case studies, real-life consulting assignments, and business scenarios, the course offers exposure to the technical, ethical, and business challenges of winning and executing environmental projects.

**Course Learning Outcomes**

- 1. Understand the drivers and policies that protect our environmental and water resources.
- 2. Apply knowledge gained in the course from pragmatic problems taken from real scenarios experienced within the consulting industry
- 3. Develop an appreciation for investigations and data interpretation making science-based decisions where possible and determine when decisions may require additional information.
- 4. Know the basic process of project initiation, budgeting, management, and effective delivery in executing environmental projects.
- 5. Work with a team to interpret given data to understand what information is important to advise alternatives, planning, decisions, and design.
- 6. Consider how to tailor designs to meet objectives that protect public health and to meet environment objectives and requirements.
- 7. Use data and engineering judgement to calculate sizing of infrastructure and to develop solutions to solve local environmental problems; research and consider social and economic project considerations and outcomes
- 8. Effectively deliver quality technical products to communicate issues and basis of design; develop communication and presentations skills that effectively share information to an appropriate audience; present technical materials to instructors and peers; provide constructive feedback to peers.

**CEEN597. SPECIAL SUMMER COURSE. 0-6 Semester Hr.**

**CEEN598. SPECIAL TOPICS IN CIVIL AND ENVIRONMENTAL ENGINEERING. 0-6 Semester Hr.**

(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**CEEN598. SPECIAL TOPICS. 0-6 Semester Hr.**

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**CEEN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**CEEN599AA. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**CEEN599AB. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**CEEN599AC. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**CEEN599AD. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**CEEN599AE. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**CEEN599AF. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**CEEN599AG. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**CEEN599AH. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**CEEN599AI. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**CEEN599AJ. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**CEEN599AK. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**CEEN599AL. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**CEEN599AM. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**CEEN599AN. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**CEEN599AO. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**CEEN599AP. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

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**CEEN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**CEEN698. SPECIAL TOPICS IN CIVIL AND ENVIRONMENTAL ENGINEERING. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**CEEN699. ADVANCED INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**CEEN699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**CEEN699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**CEEN707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.**
(I, II, S) Research credit hours required for completion of a Masters-level thesis or Doctoral dissertation. Research must be carried out under the direct supervision of the student's faculty advisor. Variable class and semester hours. Repeatable for credit.

## Department Head

D.V. Griffiths

## Professor and Associate Department Head

Jonathan O. Sharp

## Professor and Grewcock Distinguished Chair

Mike A. Mooney

## University Distinguished Professor

Christopher Higgins

## Professors

Tzahi Cath

Linda Figueroa

Terri Hogue

Amy Landis

Ning Lu

John E. McCray

Junko Munakata Marr

John R. Spear

Timothy Strathmann

## Associate Professors

Eric Anderson

Christopher Bellona

Reza Hedayat

Shiling Pei

## Assistant Professors

Yangming Shi

Lori Tunstall

## Teaching Professors

Andres Guerra

Kristoph Kinzli

Susan Reynolds

## Teaching Associate Professors

Jeffrey Holley

Hongyan Liu

Alexandra Wayllace

## Teaching Assistant Professors

Chelsea Panos

Cara Phillips

Syd Slouka

## Professor of Practice

Karen Gupta

## Emeriti Professor

Bruce Honeyman

Robert L. Siegrist

## Emeriti Associate Professor

Ronald R.H. Cohen

Panos Kiousis

## Emeritus Teaching Professor

Joseph Crocker

Candace Sulzbach

# Chemistry

## Degrees Offered

- Master of Science (Chemistry; thesis and non-thesis options)
- Doctor of Philosophy (Applied Chemistry)

## Program Description

The Department of Chemistry offers MS (thesis and non-thesis options) in Chemistry and PhD degrees in Applied Chemistry. In addition, interdisciplinary MS and PhD degrees are also offered in Geochemistry, Hydrological Sciences and Engineering, Materials Science, Nuclear Engineering, and Quantitative Biosciences and Engineering.

## Prerequisites

A candidate for an advanced degree in the Chemistry program should have completed an undergraduate program in Chemistry which is essentially equivalent to that offered by the Department of Chemistry at Colorado School of Mines. Undergraduate deficiencies will be determined by faculty in the Department of Chemistry through interviews and/or placement examinations at the beginning of the student's first semester of graduate work.

## Required Curriculum

## Chemistry

A student in the chemistry program, in consultation with the advisor and thesis committee, selects the program of study. Initially, before a thesis advisor and thesis committee have been chosen, the student is advised by a temporary advisor and by the Graduate Affairs Committee in the Department of Chemistry.

## Master of Science

**MS Degree (Chemistry, thesis option):** The program of study includes coursework, research, and the preparation and oral defense of an MS thesis based on the student's research. The required courses are:

| | | |
|---|---|---|
| CHGN502 | ADVANCED INORGANIC CHEMISTRY | 3.0 |
| CHGN503 | ADV PHYSICAL CHEMISTRY I | 3.0 |
| CHGN505 | ADVANCED ORGANIC CHEMISTRY | 3.0 |
| CHGN507 | ADVANCED ANALYTICAL CHEMISTRY | 3.0 |
| CHGN560 | GRADUATE SEMINAR (M.S.-level seminar ) | 1.0 |

A minimum of 30 credits, including at least 18 credits of coursework, is required. At least 15 of the required 18 credits of coursework must be taken in the Department of Chemistry at Mines. Only one credit of CHGN560 may be applied to the 18-credit coursework requirement. The total hours of coursework required are determined on an individual basis by the student's thesis committee.

**Research-Intensive MS Degree:** Mines undergraduates who enter the graduate program through the combined BS/MS program may use this option (thesis-based MS) to acquire a research-intensive MS degree by minimizing the time spent on coursework. This option requires a minimum of 12 hours of chemistry-focused coursework up to 6 hours of which may be double counted from the student's undergraduate studies at Mines (see below). Only one credit of CHGN560 may be applied to the 12-credit coursework requirement.

**MS Degree (Chemistry, non-thesis option):** The non-thesis MS degree requires 30 credits:

| | |
|---|---|
| Course work | 24.0 |
| Independent study | 6.0 |
| **Total Semester Hrs** | **30.0** |

The program of study includes coursework, independent study (CHGN 699) on a topic determined by the student and the student's faculty advisor, and the preparation of an oral presentation and of a report based on the student's independent study topic. The independent study could take the form of an off-campus internship under supervision of the student's advisor. As part of the 24 credits of required coursework, students must complete CHGN560 as well as three of the four core courses (CHGN502, CHGN503, CHGN505, CHGN507; 3 credits each).

| | | |
|---|---|---|
| CHGN502 | ADVANCED INORGANIC CHEMISTRY | 3.0 |
| CHGN503 | ADV PHYSICAL CHEMISTRY I | 3.0 |
| CHGN505 | ADVANCED ORGANIC CHEMISTRY | 3.0 |

| | | |
|---|---|---|
| CHGN507 | ADVANCED ANALYTICAL CHEMISTRY | 3.0 |
| CHGN560 | GRADUATE SEMINAR (M.S.-level seminar) | 1.0 |

All credits received for CHGN560 may count towards the coursework requirement for the non-thesis MS degree. At least 21 of the required 30 credits must be taken as a registered master's degree student at Mines. Up to 9 credits of graduate courses may be transferred into the degree program, provided that those courses have not been used as credit toward a Bachelor's degree. The student's committee makes decisions on courses to be taken and transfer credit and examines the student's written report and oral presentation resulting from the independent study.

**Dual Degree Program Option:** Students have the opportunity to earn two degrees with the dual degree option. Students complete coursework to satisfy requirements for both a non-thesis MS in Chemistry from the Colorado School of Mines and a Master of Science of Physical Chemistry and Chemical Physics from the University of Bordeaux.

*Seminar requirement*. All MS students are required to give a passing 20-minute CHGN560 seminar, graded by a faculty committee, before graduation. Full-time MS students are generally expected to maintain continuous enrollment in CHGN560 and are required to attend seminars.

## Mines' Combined Undergraduate / Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

## PhD Degree (Applied Chemistry)

The program of study for the PhD degree in Applied Chemistry includes coursework, a comprehensive examination, a thesis proposal, research, and the preparation and oral defense of a PhD thesis based on the student's research. The Doctor of Philosophy requires 72 credits beyond the bachelor's degree.

*Coursework*. The required courses are:

| | | |
|---|---|---|
| CHGN502 | ADVANCED INORGANIC CHEMISTRY | 3.0 |
| CHGN503 | ADV PHYSICAL CHEMISTRY I | 3.0 |
| CHGN505 | ADVANCED ORGANIC CHEMISTRY | 3.0 |
| CHGN507 | ADVANCED ANALYTICAL CHEMISTRY | 3.0 |
| CHGN560 | GRADUATE SEMINAR | 2.0 |
| **Total Semester Hrs** | | **14.0** |

PhD students must receive at minimum a B in required core classes; students who receive a B- or lower need to demonstrate subject competency to continue in the PhD program. At least 18 credits of coursework are required for the PhD degree. PhD students can count two credits of CHGN560 toward their coursework requirement. The total hours of course work required are determined on an individual basis by the student's thesis committee. Up to 24 credits of graduate-level coursework may be transferred from other institutions toward the PhD degree provided that those courses have not been used by the student toward a bachelor's degree. Up to 36 credits may be transferred if the student has completed a master's degree. The student's thesis committee may set additional course requirements and will make decisions on requests for transfer credit.

*Comprehensive examination*. The comprehensive examination comprises a written literature review of the student's field of research, an oral presentation of the literature review, and oral answers to questions posed by the audience members and the student's thesis committee. The literature review must be completed prior to the end of the student's fourth academic-year semester in the graduate program. A student's thesis committee may, at its discretion, require additional components to the comprehensive examination process.

*Seminar requirement*. Full-time PhD students are expected to maintain continuous enrollment in CHGN560 and attend seminars for four years, and should give a 40-minute seminar, graded by a faculty committee, before the end of their sixth academic-year semester in the program. They are also expected to give a conference presentation or a second public seminar before graduation.

*Thesis proposal.* A written thesis proposal must be presented to and approved by the student's thesis committee during the student's fourth year in the program or approximately one year before the anticipated thesis defense date, whichever comes earlier. The thesis proposal document should be a 2000 to 2500 word document including an introduction describing the significance and context of the thesis topic, a chapter-by-chapter description of research questions and findings, and a visual timeline specifying timeframes for data collection, analysis, and write-up of each chapter. The presentation should be 30 to 40 minutes long and is followed by questions from the general audience and the student's thesis committee. The document must be submitted at least a week prior to the scheduled presentation.

## Geochemistry

Please see the Geochemistry section of this bulletin for more information.

## Courses

**CHGN502. ADVANCED INORGANIC CHEMISTRY. 3.0 Semester Hrs.**
Detailed examination of concepts such as molecular symmetry, group theory, molecular orbital theory, ligand field theory, and crystal field theory. Additional topics include spectroscopy, inorganic reaction mechanisms, and organometallic chemistry.

**CHGN503. ADV PHYSICAL CHEMISTRY I. 3.0 Semester Hrs.**
(II) Quantum chemistry of classical systems. Principles of chemical thermodynamics. Statistical mechanics with statistical calculation of thermodynamic properties. Theories of chemical kinetics. 3 hours lecture; 3 semester hours. Prerequisite: none.

**CHGN505. ADVANCED ORGANIC CHEMISTRY. 3.0 Semester Hrs.**
Detailed discussion of the more important mechanisms of organic reaction. Structural effects and reactivity. The application of reaction mechanisms to synthesis and structure proof. Prerequisite: none. 3 hours lecture; 3 semester hours.

**CHGN507. ADVANCED ANALYTICAL CHEMISTRY. 3.0 Semester Hrs.**
(I) Review of fundamentals of analytical chemistry. Literature of analytical chemistry and statistical treatment of data. Manipulation of real substances; sampling, storage, decomposition or dissolution, and analysis. Detailed treatment of chemical equilibrium as related to precipitation, acid-base, complexation and redox titrations. Potentiometry and UV-visible absorption spectrophotometry.
Prerequisite: none. 3 hours lecture; 3 semester hours.

**CHGN508. ANALYTICAL SPECTROSCOPY. 3.0 Semester Hrs.**
(II) Detailed study of classical and modern spectroscopic methods; emphasis on instrumentation and application to analytical chemistry problems. Topics include: UV-visible spectroscopy, infrared spectroscopy, fluorescence and phosphorescence, Raman spectroscopy, arc and spark emission spectroscopy, flame methods, nephelometry and turbidimetry, reflectance methods, Fourier transform methods in spectroscopy, photoacoustic spectroscopy, rapid-scanning spectroscopy. Prerequisite: none. 3 hours lecture; 3 semester hours. Offered alternate years.

**CHGN509. BIOLOGICAL INORGANIC CHEMISTRY. 3.0 Semester Hrs.**
This course starts with a short introduction to inorganic chemistry and biology. The course then focuses on core bioinorganic chemistry topics, including metalloprotein structure and function; characterization of bioinorganic systems; metal assimilation, metabolism, and homeostasis; and metals in medicine. We also briefly cover special topics, such as metallo-endocrinology, extremophiles, biomineralization, and supramolecular bioinorganic chemistry. We investigate recent advances in the field of bioinorganic chemistry, introduce many leading scientists in the field, and explore scientific literature. Students are assessed through two open-resource, take-home exams (midterm and final) covering course material. Students also explore a topic of their choice through a class presentation and a writing assignment. There are no formal prerequisites for the class; however, students will benefit from having taken at least one of the following courses: organic chemistry, inorganic chemistry, or biochemistry.

**CHGN510. CHEMICAL SEPARATIONS. 3.0 Semester Hrs.**
(II) Survey of separation methods, thermodynamics of phase equilibria, thermodynamics of liquid-liquid partitioning, various types of chromatography, ion exchange, electrophoresis, zone refining, use of inclusion compounds for separation, application of separation technology for determining physical constants, e.g., stability constants of complexes. Prerequisite: CHGN507. 3 hours lecture; 3 semester hours. Offered alternate years.

**CHGN511. APPLIED RADIOCHEMISTRY. 3.0 Semester Hrs.**
(II) The Applied Radiochemistry course is designed for those who have a budding interest radiochemistry and its applications. A brief overview of radioactivity and general chemistry will be provided in the first three weeks of the course. Follow-on weeks will feature segments focusing on the radiochemistry in the nuclear fuel cycle, radioisotope production, nuclear forensics and the environment. 3 hours lecture and discussion; 3 semester hours. Prerequisite: CHGN 122 or CHGN 125.

**CHGN512. COLLOID AND SURFACE CHEMISTRY. 3.0 Semester Hrs.**
Introduction to colloid systems, capillarity, surface tension and contact angle, adsorption from solution, micelles and micro - emulsions, the solid/gas interface, surface analytical techniques, van der Waal forces, electrical properties and colloid stability, some specific colloid systems (clays, foams and emulsions) will be introduced.
**Course Learning Outcomes**

- Gain knowledge in fundamental chemical principles and processes occuring at interfaces.

**CHGN513. CHEMISTRY OF THE LANTHANIDES AND ACTINIDES. 3.0 Semester Hrs.**
This course is designed to introduce students to the chemistry and properties lanthanide and actinide elements, collectively known as the f-block. These elements are key components of nearly all electronic devices, and you are currently using about eight of them if you are reading this on a cellphone or computer. They also possess fascinating and complex chemistry that can be quite different from transition metals. The course will start with a history of their discovery and the developments that took place during the Manhattan Project. The course will then continue with fundamentals of f-block chemistry with a focus on electronic structure and thermodynamics. Following this, other core topics will include: 1) environmental chemistry including efforts to remediate Cold War legacy nuclear sites and how chemistry plays a role in this. 2) Aqueous Chemistry. 3) Coordination chemistry. 4) Optical and magnetic properties and the selection rules that determine these phenomena. 5) Catalysis, including small molecule activation and polymerization. 5) Separations and recycling. 6) Nuclear Medicine. Each year the course will be partially tailored to recent discoveries and adjusted in focus based on class interests.
**Course Learning Outcomes**

- At the completion of this course, students will: Have an understanding of why f-block elements are fundamentally different from elements in other parts of the periodic table.
- Understand why the unique electronic properties of f-block elements play key roles in numerous technologies.
- Understand the pros and cons of nuclear energy including the recycling and storage of nuclear waste.

**CHGN515. CHEMICAL BONDING IN MATERIALS. 3.0 Semester Hrs.**
(I) Introduction to chemical bonding theories and calculations and their applications to solids of interest to materials science. The relationship between a material's properties and the bonding of its atoms will be examined for a variety of materials. Includes an introduction to organic polymers. Computer programs will be used for calculating bonding parameters. Prerequisite: none. 3 hours lecture; 3 semester hours.

**CHGN523. SOLID STATE CHEMISTRY. 3.0 Semester Hrs.**
(I) Dependence of properties of solids on chemical bonding and structure; principles of crystal growth, crystal imperfections, reactions and diffusion in solids, and the theory of conductors and semiconductors. Prerequisite: none. 3 hours lecture; 3 semester hours. Offered alternate years.

**CHGN529. BIOCHEMISTRY II. 3.0 Semester Hrs.**
A continuation of CHGN428. Topics include: nucleotide synthesis; DNA repair, replication and recombination; transcription, translation and regulation; proteomics; lipid and amino acid synthesis; protein target and degradation; membranes; receptors and signal transduction. Prerequisite: CHGN 428.

**CHGN535. PHYSICAL BIOCHEMISTRY. 3.0 Semester Hrs.**
Apply physical chemical principles to understand property-function relationships of biochemical molecules, and investigate biochemical instrumentation and quantitative analyses common to biochemistry. Methods discussed include light/fluorescence microscopy, biomolecular structure determination, i.e., X-ray crystallography, cryo-electron microscopy and NMR, scattering techniques, biomolecular motors, and more. Prerequisite: CHGN 428 + CHGN 209 or equivalent (CBEN 210 or BIOL 301) Co-requisite: N/A.
**Course Learning Outcomes**

- 1) Demonstrate basic knowledge of thermodynamics and statistical mechanics, and their applications in biochemistry
- 2) Demonstrate basic knowledge of quantum mechanics and its applications in biochemistry
- 3) Demonstrate basic knowledge of common spectroscopic and imaging methods used in biochemistry
- 4) Develop grant-writing skills, particularly in relation to explaining scientific concepts clearly and concisely

- 5) Develop oral presentation skills when disseminating scientific information

**CHGN536. ADVANCED POLYMER SYNTHESIS. 3.0 Semester Hrs.**
(II) An advanced course in the synthesis of macromolecules. Various methods of polymerization will be discussed with an emphasis on the specifics concerning the syntheses of different classes of organic and inorganic polymers. 3 hours lecture, 3 semester hours Prerequisite: CHGN 430, CBEN 415, MLGN 530.

**CHGN538. ORGANIC SEMICONDUCTORS: NEW TECHNOLOGIES FOR EMERGING APPLICATIONS. 3.0 Semester Hrs.**
(II) Organic Light Emitting Diodes (OLEDs) is a display technology that can be found in many commercial products such as the smartphones and tablets. This technology was on the R&D bench-top just 10 years ago and has now reached high volume manufacturing. Other related technologies like organic photovoltaics (OPV) and organic thin film transistors (OTFT) are now on the heels of commercialization as well. This course will provide an overview on how this meteoric rise from bench-top to commercial products occurred as well as the design, synthesis and uses of conjugated organic small molecules, oligomers and polymers in applications such as OLEDs (for flat panel displays and lighting), OPV, OTFT, and sensors. Additional topics to be covered are factors governing the materials physical properties and structure-property relationship in electronic device applications. The prospect of using low cost printing techniques such as inkjet, screen, and gravure printing in the fabrication of roll-to-roll organic based devices will be discussed. Encapsulation, lifetime and reliability issues will also be presented. Prerequisites: Organic Chemistry 1 & 2 are encouraged. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Ability to apply the knowledge on Organic Semiconductors and Structure-Property relationships to future research and engineering problems

**CHGN540. PROFESSIONAL SKILLS FOR CHEMICAL SCIENTISTS. 1.0 Semester Hr.**
The goal of this course is to provide students a set of skills that are complementary to their core education. The contents of this course cover a broad range of topics that will provide the participants a perspective on careers in science and the skill sets necessary to be successful in each. These skills are in line with the latest recommendations of the American Chemical Society (ACS) and CSM educational goals. In particular, the 2013 ACS Presidential Commission Report on Graduate Education in the Chemical Sciences presents a platform for educational reform that includes a focus on multi-level (from general public to specialists) and multi-platform communication (formal and informal, written, oral), an understanding of the global chemical enterprise and the career possibilities within each, an understanding of networking and collaboration, etc. 1 hour lecture; 1 semester hour.

**CHGN545. CHEMICAL BIOLOGY. 3.0 Semester Hrs.**
The analysis of biological systems from the perspective of organic/inorganic and physical chemistry, including chemical reactions for the synthetic preparation of biomolecules and the chemistry behind different biotechnological developments and tools. A strong emphasis on the mechanistic basis of biochemical transformations is included. Strategies for directing pharmaceuticals or diagnostics to different subcellular locales will be presented. A survey of key advancements in the field of chemical biology will be drawn from the primary literature. Prerequisite: CHGN 222, CHGN 428.

**CHGN555. POLYMER AND COMPLEX FLUIDS COLLOQUIUM. 1.0 Semester Hr.**
Equivalent with CBEN555,MLGN555,
The Polymer and Complex Fluids Group at the Colorado School of Mines combines expertise in the areas of flow and field based transport, intelligent design and synthesis as well as nanomaterials and nanotechnology. A wide range of research tools employed by the group includes characterization using rheology, scattering, microscopy, microfluidics and separations, synthesis of novel macromolecules as well as theory and simulation involving molecular dynamics and Monte Carlo approaches. The course will provide a mechanism for collaboration between faculty and students in this research area by providing presentations on topics including the expertise of the group and unpublished, ongoing campus research. Prerequisites: none. 1 hour lecture; 1 semester hour. Repeatable for credit to a maximum of 3 hours.

**CHGN560. GRADUATE SEMINAR. 1.0 Semester Hr.**
Required for all candidates for the M.S. and Ph.D. degrees in Chemistry. Full-time graduate students resident on campus must register for the course during each semester of their first four years of residency. Attendance at most departmental seminars is required, and all graduate students are required to present a departmental seminar. Prerequisite: Enrollment in Chemistry M.S. or Ph.D. degree program.

**CHGN580. STRUCTURE OF MATERIALS. 3.0 Semester Hrs.**
(II) Application of X-ray diffraction techniques for crystal and molecular structure determination of minerals, inorganic and organometallic compounds. Topics include the heavy atom method, data collection by moving film techniques and by diffractometers, Fourier methods, interpretation of Patterson maps, refinement methods, direct methods. Prerequisite: none. 3 hours lecture; 3 semester hours. Offered alternate years.

**CHGN581. ELECTROCHEMISTRY. 3.0 Semester Hrs.**
(I) Introduction to theory and practice of electrochemistry. Electrode potentials, reversible and irreversible cells, activity concept. Interionic attraction theory, proton transfer theory of acids and bases, mechanisms and fates of electrode reactions. Prerequisite: none. 3 hours lecture; 3 semester hours. Offered alternate years.

**CHGN583. PRINCIPLES AND APPLICATIONS OF SURFACE ANALYSIS TECHNIQUES. 3.0 Semester Hrs.**
(II) Instrumental techniques for the characterization of surfaces of solid materials; Applications of such techniques to polymers, corrosion, metallurgy, adhesion science, microelectronics. Methods of analysis discussed: x-ray photoelectron spectroscopy (XPS), auger electron spectroscopy (AES), ion scattering spectroscopy (ISS), secondary ion mass spectrometry (SIMS), Rutherford backscattering (RBS), scanning and transmission electron microscopy (SEM, TEM), energy and wavelength dispersive x-ray analysis; principles of these methods, quantification, instrumentation, sample preparation. 3 hours lecture; 3 semester hours. Prerequisite: B.S. in Metallurgy, Chemistry, Chemical Engineering, Physics, or consent of instructor.

**CHGN584. FUNDAMENTALS OF CATALYSIS. 3.0 Semester Hrs.**
(II) The basic principles involved in the preparation, characterization, testing and theory of heterogeneous and homo geneous catalysts are discussed. Topics include chemisorption, adsorption isotherms, diffusion, surface kinetics, promoters, poisons, catalyst theory and design, acid base catalysis and soluble transition metal complexes. Examples of important industrial applications are given. Prerequisite: CHGN222. 3 hours lecture; 3 semester hours.

**CHGN585. CHEMICAL KINETICS. 3.0 Semester Hrs.**
(II) Study of kinetic phenomena in chemical systems. Attention devoted to various theoretical approaches. Prerequisite: none. 3 hours lecture; 3 semester hours. Offered alternate years.

**CHGN597. SPECIAL RESEARCH. 0-15 Semester Hr.**

**CHGN598. SPECIAL TOPICS IN CHEMISTRY. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**CHGN598. SPECIAL TOPICS. 0-6 Semester Hr.**

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**CHGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**CHGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

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**CHGN625. MOLECULAR SIMULATION. 3.0 Semester Hrs.**
Principles and practice of modern computer simulation techniques used to understand solids, liquids, and gases. Review of the statistical foundation of thermodynamics followed by indepth discussion of Monte Carlo and Molecular Dynamics techniques. Discussion of intermolecular potentials, extended ensembles, and mathematical algorithms used in molecular simulations. 3 hours lecture; 3 semester hours. Prerequisite: CBEN 509 or equivalent, and recommend CBEN 610 or equivalent.

**CHGN698. SPECIAL TOPICS IN CHEMISTRY. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**CHGN699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research, special problem projects, or internship supervised by a Chemistry faculty member, with student and instructor agreeing on a subject matter, content, deliverables, and credit hours. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree. Prerequisites: “Independent Study” form must be completed and submitted to the Registrar.

**CHGN699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research, special problem projects, or internship supervised by a Chemistry faculty member, with student and instructor agreeing on a subject matter, content, deliverables, and credit hours. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**CHGN707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.**
(I, II, S) Research credit hours required for completion of a Masters-level thesis or Doctoral dissertation. Research must be carried out under the direct supervision of the student's faculty advisor. Variable class and semester hours. Repeatable for credit.

## Professors

Thomas Albrecht

Thomas Gennett, Department Head

Richard C. Holz, Provost

Mark P. Jensen, Grandey University Chair in Nuclear Science & Engineering

Daniel M. Knauss, Associate Dean of Energy and Materials

Matthew C. Posewitz

James F. Ranville

Ryan M. Richards

Alan S. Sellinger

Jenifer C. Shafer

Bettina M. Voelker

Shubham Vyas

## Associate Professors

Dylan Domaille

Svitlana Pylypenko

Brian G. Trewyn

## Assistant Professors

David Halat

Samantha Johnson

Annalise Maughan

C. Michael McGuirk

## Teaching Professors

Renee L. Falconer, Assistant Department Head

Angela Sower

## Teaching Associate Professors

Amanda Jameer

Erik Menke

### Teaching Assistant Professors

Christian Beren

Amanda Furness

Jonathan Miorelli

Megan Moyer

### Research Professors

Mark E. Eberhart

Kim R. Williams

### Research Associate Professors

Nicholas Bedford

Jessica Jackson

Yuan Yang

### Research Assistant Professors

Shane Galley

Joseph Sperling

### Adjunct Faculty

Laurel Almer

### Joint Appointees

Mark Allendorf

Matthew Beard

Todd Deutsch

Lieve Laurens

Bryan Pivovar

Daniel Ruddy

Rebecca Smaha

### Affiliated Faculty

Judah Friese

Joseph Meyer

Nicholas Strange

John Stringer

Liz Ware

### Professor Emeriti

Scott W. Cowley

Mark E. Eberhart

Ronald W. Klusman

Donald Langmuir

Donald L. Macalady

Patrick MacCarthy

Michael J. Pavelich

Mark R. Seger

E. Craig Simmons

Kent J. Voorhees

Thomas R. Wildeman

Kim Williams

David Wu

# Computer Science

## Degrees Offered

- Master of Science (Computer Science)
- Doctor of Philosophy (Computer Science)
- Professional Master's Degree - Online
- Graduate Certificate in Cybersecurity

## Program Overview

The Computer Science Department offers the Master of Science and Doctor of Philosophy in Computer Science. These degree programs demand academic rigor and depth yet also address real-world problems.

The department’s research falls into six areas: algorithms, human-centered computing, machine learning and data science, robotics, security and privacy. The Department of Computer Science has a strong emphasis on research, both within the department and collaboratively with other departments, universities, government organizations and industry partners. See the CS@Mines Research webpage for updated details and current projects: https://cs.mines.edu/research/.

## PROGRAM DETAILS

The Computer Science Department offers a variety of programs:

We offer the degrees Master of Science and Doctor of Philosophy in Computer Science. The master's program is designed to prepare candidates for careers in industry or government or for further study at the PhD level; both thesis and non-thesis options are available. The PhD degree program is sufficiently flexible to prepare candidates for careers in industry, government, or academia.

*Combined Program:* The CS Department also offers combined BS/MS degree programs. These programs offer an expedited graduate school application process and allow students to begin graduate coursework while still finishing their undergraduate degree requirements.

## Admission PREREQUISITES

### BS+MS Combined

Current Mines undergraduate students are encouraged to apply for the combined program once they have taken five or more Computer Science classes at Mines (classes transferred from other universities will not be considered). This requirement may be met by any 200-level or above

course with a CSCI prefix (e.g., CSCI200, CSCI306, CSCI406 CSCI442, etc.), excluding CSCI274, CSCI370, CSCI499.

Students should have an overall GPA of at least 3.0 and a GPA of 3.2 for courses in the major. The calculation of GPA in the major will be based on *all* 200-level or above CSCI courses except those excluded above (i.e., CSCI274, CSCI370 and CSCI499). If a course is taken multiple times, all of the grades will be included into the GPA calculation. Interested students with a lower GPA must include in their statement of goals/personal statement a section explaining why they should be admitted to the program.

## GRADUATE CERTIFICATE IN CYBERSECURITY

The minimum requirements for admission to the Graduate Certificate in CyberSecurity are:

- Undergraduate-level knowledge on data structures, computer organization, algorithms, and operating systems.
- Undergraduate-level knowledge on statistics and discrete mathematics.
- Undergraduate-level skills on the Linux operating system and shell scripts.
- Undergraduate-level programming skills in languages such as C, C++, Python, Java, JavaScript, and HTML/CSS.

## MASTER'S AND PHD

The minimum requirements for admission to the MS and Ph.D degrees in Computer Science are:

- Applicants must have a bachelor's degree, or equivalent, from an accredited institution with a grade-point average of 3.0 or better on a 4.0 scale.
- Students are expected to have completed the following coursework at Mines or equivalent at another institution: 1) CSCI200 FOUNDATIONAL PROGRAMMING CONCEPTS & DESIGN: Foundational Programming Concepts and Design, 2) CSCI220: Data Structures and Algorithms, 3) CSCI306: Software Engineering, 4) CSCI341: Computer Organization, 5) CSCI358: Discrete Mathematics. It is strongly suggested applicants also have completed a course in Algorithms and Operating Systems. The CS graduate admissions committee will require that students who do not meet this expectation demonstrate competency or take remedial coursework. Such coursework will not count toward the graduate degree. The committee will decide whether to recommend regular or provisional admission.
- TOEFL score of 79 or higher (or 550 for the paper-based test or 213 for the computer-based test) for applicants whose native language is not English. In lieu of a TOEFL score, and IELTS score of 6.5 or higher will be accepted.
- For the PhD program, prior research experience is desired but not required.

*Admitted Students:* The CS Department Graduate Committee may require that an admitted student take undergraduate remedial coursework to overcome technical deficiencies. The committee will decide whether to recommend regular or provisional admission.

*Transfer Courses:* Graduate-level courses taken at other universities for which a grade equivalent to a B or better was received will be considered for transfer credit with approval of the advisor and/or thesis committee, and CS department head, as appropriate. Transfer credits must not have been used as credit toward a Bachelor degree. For the MS degree, no more than nine credits may transfer. For the PhD degree, up to 24 credits may be transferred. In lieu of transfer credit for individual courses, students who enter the PhD program with a thesis-based master's degree from another institution may transfer up to 36 credits in recognition of the coursework and research completed for that degree.

*Advisor and Thesis Committee:* Students must have an advisor from the CS faculty to direct and monitor their academic plan, research, and independent studies. Advisors must be full-time permanent members of the faculty. In this context, full-time permanent members of the faculty are those that hold the rank of professor, associate professor, assistant professor, research professor, associate research professor or assistant research professor. Upon approval by the graduate dean, adjunct faculty, teaching faculty, visiting professors, emeritus professors, and off-campus representatives may be designated additional co-advisors. A list of CS faculty by rank is available in the faculty tab of the catalog.

Master of Science (thesis option) students in CS must have at least three members on their thesis committee; the advisor and one other member must be permanent faculty in the CS Department. CS PhD thesis committees must have at least four members; the advisor/co-advisor and two additional members must be permanent faculty in the CS Department, and one member must be outside the departmental faculty and serving as chair of the committee. Students who choose to have a minor program must select a representative from the minor area of study to serve on the thesis committee.

*Degree Audit and Admission to Candidacy:* Master's students must complete the Degree Audit form by the posted deadline. PhD students need to submit the Degree Audit form by the posted deadline and need to submit the Admission to Candidacy form by the posted deadline of the semester in which they want to be considered eligible for reduced registration.

*Time Limit:* As stipulated by the Mines Graduate School, a candidate for a master's degree must complete all requirements for the degree within five years of the date of admission into the degree program. A candidate for a doctoral degree must complete all requirements for the degree within nine years of the date of admission into the degree program.

## PROGRAM REQUIREMENTS

### Mines' Combined Undergraduate/Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework (500-level or above) to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

Current Mines undergraduate students are encouraged to apply for the combined program once they have taken five or more Computer Science classes at Mines (classes transferred from other universities will not be considered). This requirement may be met by any 200-level or above course with a CSCI prefix (e.g., CSCI200, CSCI306, CSCI406, CSCI442, etc.), excluding CSCI274, CSCI370, and CSCI499. Students should

have an overall GPA of at least 3.0 and a GPA of 3.2 for courses in the major. The calculation of GPA in the major will be based on all 200-level or above CSCI courses except those excluded above (i.e., CSCI274, CSCI370 and CSCI499). If a course is taken multiple times, all of the grades will be included into the GPA calculation. Interested students with a lower GPA must include in their statement of goals/personal statement a section explaining why they should be admitted to the program.

## Master of Science - Computer Science

The MS degree in Computer Science (thesis or non-thesis option) requires 30 credits. Requirements for the thesis MS are 21 hours of coursework plus 9 hours of thesis credit leading to an acceptable master's thesis; thesis students are encouraged to find a thesis advisor and form a thesis committee by the end of the first year. The non-thesis option consists of two tracks: a Project Track and a Coursework Track.

Requirements for the Project Track are 24 hours of coursework plus 6 hours of project credit; requirements for the Coursework Track are 30 hours of coursework. The following two core courses are required of all students. Students may choose elective courses from any CSCI graduate course offered by the department. In addition, up to 6 credits of elective courses may be taken outside of CSCI. Lastly, a maximum of six independent study course units can be used to fulfill degree requirements. Core courses for the program are below. CSCI 561 and CSCI 564 (or an alternative course, subject to approval by the committee based on the provided justification). Examples of potential alternative courses include CSCI 582 (Computing Beyond CPUs), CSCI 565 (Distributed Computing), and CSCI 563 (Parallel Computing for Scientists and Engineers)..

| | | |
|---|---|---|
| CSCI561 | THEORY OF COMPUTATION (offered every fall) | 3.0 |
| CSCI564 | ADVANCED COMPUTER ARCHITECTURE (offered every spring) | 3.0 |

### MS Project Track

Students are required to take 6 credits of CSCI700 to fulfill the MS project requirement. (It is recommended that the 6 credits consist of two consecutive semesters of 3 credits each.) At most, 6 credits of CSCI700 will be counted toward the masters non-thesis degree. Deliverables include a report and a presentation to a committee of two CS faculty including the advisor. Deliverables must be successfully completed in the last semester in which the student registers for CSCI700. A student must receive two pass votes (i.e., a unanimous vote) to satisfy the project option.

### MS Thesis Defense

At the conclusion of the MS thesis, the student will be required to make a formal presentation and defense of her/his thesis research. A student must pass this defense to earn an MS degree.

### CS Minor

A CS Minor at the master's level requires a minimum of 9 credits of CSCI coursework, of which at least 6 credits of coursework must be at the 500-level or above excluding independent studies and graduate seminars. Pursuant to Graduate School rules, all minors must be approved by the student's advisor, home department head, and a faculty representative of the minor area of study. A minor may not be taken in the student's major area of study.

### CS@Mines Bridge Program

The Bridge Program is designed for those without a background in CS to have a direct pathway to a Computer Science (CS) master's (MS) degree. Students in the CS@Mines Bridge program will complete foundational undergraduate courses which will prepare them for master's level coursework. Students will then continue to the MS non-thesis (NT) program as a full-time or part-time student.

All incoming Bridge students are required to have earned a bachelor's degree from an accredited with a grade-point average of at least 3.0 on a 4.0 scale.

Bridge students are required to take a set of pre-requisite Bridge courses to prepare for the MS degree. Required courses are CSCI195, CSCI200, CSCI210, CSCI220, CSCI306, CSCI341, and CSCI358. Incoming students with no completed coursework in calculus or programming from an accredited institution may need to take Calculus 1-3 and CSCI128 in addition to the Bridge courses stated above. Students must earn a B or higher in their Bridge coursework for it to count toward their progress in the program.

For more information regarding the program and application process, please contact our Graduate Program Manager, Kelsie Diaz, at kdiaz@mines.edu.

## Doctor of Philosophy - Computer Science

The PhD degree in Computer Science requires 72 credits of coursework and research credits. Required coursework provides a strong background in computer science. A course of study leading to the PhD degree can be designed either for the student who has completed the master's degree or for the student who has completed the bachelor's degree. The following three courses are required of all students. Students who have taken equivalent courses at another institution may satisfy these requirements by transfer. Core courses for the program are below. CSCI 561 and CSCI 564 (or an alternative course, subject to approval by the committee based on the provided justification). Examples of potential alternative courses include CSCI 582 (Computing Beyond CPUs), CSCI 565 (Distributed Computing), and CSCI 563 (Parallel Computing for Scientists and Engineers).

| | | |
|---|---|---|
| CSCI561 | THEORY OF COMPUTATION (offered every fall) | 3.0 |
| CSCI564 | ADVANCED COMPUTER ARCHITECTURE (offered every spring) | 3.0 |
| SYGN502 | INTRODUCTION TO RESEARCH ETHICS | 1.0 |

### PhD Qualifying Examination

Students desiring to take the PhD qualifying exam must have:

- If required by your advisor, taken SYGN501: The Art of Science (previously or concurrently).
- Completed (previously or concurrently) all core courses.
- Complete (previously or concurrently) at least four CSCI 500-level courses at Mines (only one CSCI599 is allowed).
- Maintained a GPA of 3.5 or higher in all CSCI 500-level courses taken.

The PhD qualifying exam must be passed no later than the fourth semester of study. Exception must be formally requested via email to the qualifying exam committee chair and approved by the graduate committee. The PhD qualifying exam is offered once a semester. Each

PhD qualifying exam comprises of two research areas, chosen by the student. The exam consists of the following steps:

Step 1. A student indicates intention to take the CS PhD qualifying exam by choosing two research interest areas.

- The primary test area should be the same as the research area of the student's (potential) advisor. This exam will be more open-ended research than the second test area. A formal written report and a formal presentation meeting are required for this exam. The outcome of this exam can be part of the student's dissertation research. In fact, the student is strongly encouraged to create results that can lead to a publication. It is acceptable and encouraged if the advisor is involved to provide suggestions. The student is required to clearly document in the written report how the advisor was involved in the exam.
- The second test area should be from another research area of interest to the student that is 1) supported by faculty within the CS department and 2) different from the student's primary advisor's research area. It is highly recommended that the student choose their secondary test area with an instructor the student has had in one or more courses. This exam will likely be less substantial than the primary exam, i.e., instructions will be more concrete. The purpose of having a second test area is to ensure students can demonstrate both the breadth of knowledge and the capability in doing independent research. Thus, no faculty member is allowed to assist the student in this second exam except for answering clarification questions.

Students must inform the CS Qualifying Committee Chair of their intention to take the exam by a specific date provided by the Chair in the prior semester.

Step 2. The qualifying exam committee chair creates an exam committee of (at least) four appropriate faculty. The exam committee assigns the student specific tasks with corresponding deliverables for both research areas chosen. The tasks will be some combination from the following list:

- design and evaluate new algorithms or systems for an important research problem, and write a report that summarizes the design and the evaluation results.
- read a set of technical papers, write a summary of the papers read, make a presentation, and answer questions (presentations will be limited to 30-minutes with a hard stop not including Q&A).
- complete a hands-on activity (e.g., develop research software) and write a report that explains the difficulties with the activity and what was learned.
- complete a set of take-home problems.
- write a literature survey (i.e., track down references, separate relevant from irrelevant papers).

Step 3. The student must complete all deliverables no later than the Monday of review week (11:59 p.m.). Failure to meet the deadline is considered a failed attempt. The submitted report on the deadline is considered to be final, i.e., no update is allowed after the due date/time. The oral presentation will be scheduled during Finals Week. Before the oral presentation, the student is not allowed to practice the exam presentation with his/her advisor or research group to get feedback. The student will access exam problems, and submit deliverables through a specified system such as Canvas course/module. Additionally, the specified system will be used to deliver feedback from the committee to the student outlining strengths, weaknesses, recommendations and exam results.

Step 4. Each member of the exam committee makes a recommendation on the deliverables from the following list: strongly support, support, and do not support. To pass the PhD qualifying exam, the student must have at least two "strongly supports" and no more than one "do not support." If a student receives two or more "do not support" votes by the committee members, the student fails the exam. All other cases other than pass or fail are considered as conditional pass.

Conditional Pass Requirements

If a student receives a conditional pass, the student is required to take (an) additional test(s). The exam committee will explicitly specify the deadline for the student to take the additional test in the feedback comments to the student. The deadline will likely be in the beginning weeks of the following semester. The additional test(s) may be the whole or part(s) of the original qualifying exam or may be an additional task, as determined by the exam committee. If the student passes the assigned additional test, the conditional pass will be converted into a pass; otherwise, the outcome of the qualifying exam will be a fail.

The student is informed of the qualifying exam decision (pass, fail, or conditional pass) no later than the Monday after finals week. The student is informed of the outcome of a conditional pass test within two weeks after the test. A student can only fail the exam one time. If a second failure occurs, the student has unsatisfactory academic performance that results in an immediate, mandatory dismissal of the graduate student from the PhD program.

PhD Thesis Proposal: After passing the qualifying exam, the PhD student is allowed up to 18 months to prepare a written thesis proposal and present it formally to the student’s thesis committee and other interested faculty.

Admission to Candidacy: In addition to the Graduate School requirements, full-time PhD students must complete the following requirements within two calendar years of enrolling in the PhD program.

- Have a thesis committee appointment form on file in the Graduate Office.
- Have passed the PhD qualifying exam demonstrating adequate preparation for, and satisfactory ability to conduct doctoral research.

PhD Thesis Defense: At the conclusion of the student’s PhD program, the student will be required to make a formal presentation and defense of her/his thesis research. A student must pass this defense to earn a PhD degree.

## CS Minor

A CS Minor at the PhD level requires a minimum of 12 credits of CSCI coursework, of which 9 credits of coursework must be at the 500-level or above excluding independent studies and graduate seminars. Pursuant to Graduate School rules all minors must be approved by the student's advisor, home department head, and a faculty representative of the minor area of study. A minor may not be taken in the student's major area of study.

# PROFESSIONAL MASTERS DEGREE IN COMPUTER SCIENCE

To earn a professional master's (MP-CS) degree, students must complete 30 credits as outlined below. The program is composed of four flexible tracks from the options listed. To complete the 30 credit hours, students would be required to complete any 3 tracks, along with an additional elective course. The required elective course may be fulfilled by any CSCI course from the track options listed if it is not being used to complete one of their chosen tracks. At least 7 out of 10 required courses MUST be CSCI/DSCI. Students may enroll in the professional master's program from the outset and take courses from the various tracks in any order.

- All courses are delivered online; however, students interested in on-campus classes may substitute one course per track with a pre-approved CSCI elective listed in our Graduate Catalog.
- As we develop more courses for our professional master's program, we may decide that some of these courses are not appropriate for our in-residence graduate MS and PhD students and therefore may restrict registration to only MP-CS students.

Our plan is to have the Professional Master's program ready to launch in Fall 2025. We will increase the number of courses available for the MP-CS degree over the coming semesters to give both students and faculty more flexibility with offerings. Currently, the plan for our program for Fall 2025 will consist of the following courses and tracks (**bold** indicates course(s) to be developed over the next 9 months):

**Track 1: Applied Machine Learning**

The track in Applied Machine Learning is targeted to train recent graduates or mid-career professionals with a bachelor's degree in computer science or other STEM-related field with acquired basic knowledge in programming, data structures, statistics, and linear algebra.

To complete the track in Applied Machine Learning, students must complete 9 hours of coursework as follows:

- **Required Courses**
  - DSCI 503: Advanced Data Science
  - DSCI 570: Machine Learning
- **Pick one from the following:**
  - DSCI 530: Statistical Methods
  - DSCI 575: Advanced Machine Learning
  - **CSCI 578: Bioinformatics (Assignments are geared towards analytics *)**
  - **CSCI 507: Computer Vision (Assignments are geared towards analytics *)**

** Note: The assignments are focused on applying analytical techniques and methodologies, with an emphasis on data analysis, interpretation, and deriving insights from data. They are designed to develop students' skills in exploring, processing, and making data-driven decisions using various tools and frameworks commonly used in analytics.*

**Track 2: Cybersecurity**

The track in Cybersecurity is targeted to train recent graduates or mid-career professionals with a bachelor's degree in computer science or a related field with a foundational knowledge in programming, data structures, algorithms, systems programming, statistics, and discrete math.

To complete the track in Cybersecurity, students must complete 9 hours of coursework as follows:

- **Required Courses**
  - CSCI 574: Theory of Cryptography
  - CSCI 585: Information Security and Privacy
- **Pick one from the following:**
  - CSCI 560: Fundamentals of Computer Networks
  - CSCI 587: Cyber Physical Systems Security

**Track 3: Analytics and Project Management**

The track in Analytics and Project Management is targeted to train recent graduates or mid-career professionals with a bachelor's degree in computer science or other STEM-related field with acquired basic knowledge in programming, data structures, statistics, and linear algebra.

To complete the track in Analytics and Project Management, students must complete 9 hours of coursework as follows

- **Required Course:**
  - EBGN 525: Business Analytics
- **Pick one from the following:**
  - EBGN553: Project Management
  - EBGN 563: Management of Technology and Innovation (taught by Scott Houser)
  - EBGN 565: Marketing for Technology-based companies
  - EBGN 571: Marketing Analytics
  - EBGN 577: Leading and Managing High Performance Teams

*Projects in these courses would focus on software development or data science/machine learning, with an emphasis on requiring more in-depth software development and analysis. As the online program expands, we plan to add more computer science-oriented courses to this certificate track, such as cybersecurity leadership and operations.*

**Track 4: #Advanced Software Technologies**

The track in Advanced Software Technologies is targeted to train recent graduates or mid-career professionals with a bachelor's degree in computer science or other STEM-related field with acquired basic knowledge in programming, data structures, and software engineering.

To complete the track in Advanced Software Technologies, students must complete 9 hours of coursework as follows:

- **Required Course:**
  - **CSCI 5xx: Advance Software Techniques and Project Development**
- **Pick two from the following. Note that these courses would center around major software projects:**
  - **CSCI 578: Bioinformatics (Assignments are geared towards software design ^)**
  - **CSCI 507: Computer Vision (Assignments are geared towards software design ^)**

^ *Note: The assignments are focused on developing and applying software design principles, emphasizing the creation of robust, scalable, and efficient systems. They are designed to enhance students' skills in structuring, designing, and implementing software solutions, while considering best practices, design patterns, and user needs within real-world scenarios.*

Of the courses included in our four tracks, all except 'Advanced Software Techniques and Project Development' already exist in our in-person or online curriculum.

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During the 2025-2026 academic year, we plan to develop additional courses in consultation with our external advisory committee to address the high priority needs of working professionals. Based on ongoing discussions, we envision offering the following courses to our MP-CS students.

Key: All courses will be [3.0 credit hours]. Courses with a 5xx are proposed and are in various stages of discussion for development (e.g., **bold**: priority courses, *Italic*: aspirational courses)

**Track 1: Applied Machine Learning**

The track in Applied Machine Learning is targeted to train recent graduates or mid-career professionals with a bachelor's degree in computer science or other STEM-related field with acquired basic knowledge in programming, data structures, statistics, and linear algebra.

To complete the track in Applied Machine Learning, students must complete 9 hours of coursework as follows:

- **Required Courses**
  - DSCI 503: Advanced Data Science
  - DSCI 570: Machine Learning
- **Pick one from the following:**
  - DSCI 530: Statistical Methods
  - DSCI 575: Advanced Machine Learning
  - **CSCI 578: Bioinformatics (Assignments are geared towards analytics *)**
  - **CSCI 507: Computer Vision (Assignments are geared towards analytics *)**
  - *CSCI 504: Artificial Intelligence*

* Note: The assignments are focused on applying analytical techniques and methodologies, with an emphasis on data analysis, interpretation, and deriving insights from data. They are designed to develop students' skills in exploring, processing, and making data-driven decisions using various tools and frameworks commonly used in analytics.

**Track 2: Cybersecurity** -

The track in Cybersecurity is targeted to train recent graduates or mid-career professionals with a bachelor's degree in computer science or a related field with a foundational knowledge in programming, data structures, algorithms, systems programming, statistics, and discrete math.

To complete the track in Cybersecurity, students must complete 9 hours of coursework as follows:

- **Required Courses**
  - CSCI 574: Theory of Cryptography
  - CSCI 585: Information Security and Privacy
- **Pick one from the following:**
  - CSCI 560: Fundamentals of Computer Networks
  - CSCI 587: Cyber Physical Systems Security
  - *CSCI 5xx: Cybersecurity Leadership and Operations (this course is added to help prepare students for the CISSP exam from ISC2).*

**Track 3: Analytics and Project Management**

The track in Analytics and Project Management is targeted to train recent graduates or mid-career professionals with a bachelor's degree in computer science or other STEM-related field with acquired basic knowledge in programming, data structures, statistics, and linear algebra.

To complete the track in Analytics and Project Management, students must complete 9 hours of coursework as follows:

- **Required Course:**
  - EBGN 525: Business Analytics (python-based intro to DS)
- **Pick one from the following:**
  - EBGN 553: Project Management
  - EBGN 563: Management of Technology and Innovation (taught by Scott Houser)
  - EBGN 565: Marketing for Technology-based companies
  - EBGN 571: Marketing Analytics
  - EBGN 577: Leading and Managing High Performance Teams

- *CSCI 5xx: Cybersecurity Leadership and Operation (see note above under track 2) The course has a business management aspect that could allow it to fit in this track as well as the Cybersecurity track)*
- *EBGN 5xx: Innovation & Entrepreneurship in Engineering & Technology*

*Projects in these courses would focus on software development or data science/machine learning, with an emphasis on requiring more in-depth software development and analysis. As the online program expands, we plan to add more computer science-oriented courses to this certificate track, such as cybersecurity leadership and operations.*

**Track 4: Advanced Software Technologies**

The track in Advanced Software Technologies is targeted to train recent graduates or mid-career professionals with a bachelor's degree in computer science or other STEM-related field with acquired basic knowledge in programming, data structures, and software engineering.

To complete the track in Advanced Software Technologies, students must complete 9 hours of coursework as follows:

- **Required Course:**
  - **CSCI 5xx: Advance Software Techniques and Project Development**
- **Pick two from the following:**
  - CSCI 5xx: Verification, Testing, Quality Assurance
  - **CSCI 578: Bioinformatics (Assignments are geared towards software design ^)**
  - **CSCI 507: Computer Vision (Assignments are geared towards software design^)**
  - *CSCI 5xx: UI / UX*
  - *CSCI 5xx: Mobile App Development*
  - *CSCI 5xx: Cloud Computing*
  - *CSCI 5xx: Web Programming and Applications*

^ Note: The assignments are focused on developing and applying software design principles, emphasizing the creation of robust, scalable, and efficient systems. They are designed to enhance students' skills in structuring, designing, and implementing software solutions, while considering best practices, design patterns, and user needs within real-world scenarios.

# Graduate Certificate in Cybersecurity

The online Graduate Certificate in Cybersecurity is targeted to train recent graduates or mid-career professionals with a bachelor's degree in computer science or a related field with a foundational knowledge in programming, data structures, algorithms, systems programming, statistics, and discrete math.

To complete the online Graduate Certificate in Cybersecurity, students must complete 9 hours of coursework as follows:

- Required Courses:
  - o CSCI 574: Theory of Cryptography
  - o CSCI 585: Information Security and Privacy
- Pick one from the following:
  - o CSCI 560: Fundamentals of Computer Networks
  - o CSCI 587: Cyber Physical Systems Security

While all courses are to be delivered online, students that are interested in attending an on-campus class may substitute one of the above courses with a pre-approved elective as listed in our Graduate Catalog.

FUTURE PLANS

In the 2025-2026 academic year, we aim to expand our course offerings in collaboration with our external advisory committee to meet the evolving needs of working professionals. Based on our ongoing conversations, we plan to introduce a new course focused on Cybersecurity Leadership and Operations to address key industry priorities. This course, designed to support students in preparing for the CISSP exam from ISC2, will complement the following curriculum:

- Required Courses:
  - o CSCI 574: Theory of Cryptography
  - o CSCI 585: Information Security and Privacy
- Pick one from the following:
  - o CSCI 560: Fundamentals of Computer Networks
  - o CSCI 587: Cyber Physical Systems Security
  - o CSCI 5xx: Cybersecurity Leadership and Operations (this course is added to help prepare students for the CISSP exam from ISC2).

## Courses

**CSCI500. GRADUATE SEMINAR. 0.0 Semester Hrs.**
This zero-credit graduate course builds on the CS department seminars in the colloquium series, which consist of presentations delivered by external or internal invited speakers on topics broadly related to computer science. The seminar is mandatory for all Ph.D. students. The students are required to enroll in the course every semester. Any student who cannot take the course for valid reasons should notify their advisor, who will then make a request to the CS graduate committee for a waiver. These requests could be for the duration of one semester or longer. The course will be graded as PRG/PRU based on student attendance at the department seminars in the colloquium series - the student has to attend at least two thirds of all the seminars each semester in order to get a PRG grade.
**Course Learning Outcomes**

**CSCI507. INTRODUCTION TO COMPUTER VISION. 3.0 Semester Hrs.**
Equivalent with CSCI437,CSCI512,EENG507,EENG512,
(I) Computer vision is the process of using computers to acquire images, transform images, and extract symbolic descriptions from images. This course provides an introduction to this field, covering topics in image formation, feature extraction, location estimation, and object recognition.

Design ability and hands-on projects will be emphasized, using popular software tools. The course will be of interest both to those who want to learn more about the subject and to those who just want to use computer imaging techniques. 3 hours lecture; 3 semester hours. Prerequisite: Undergraduate level knowledge of linear algebra, statistics, and a programming language.

**Course Learning Outcomes**

- 1. Be able to analyze and predict the behavior of image formation, transformation, and recognition algorithms
- 2. Be able to design, develop, and evaluate algorithms for specific applications
- 3. Be able to use software tools to implement computer vision algorithms
- 4. Communicate (in oral and written form) methods and results to a technical audience

**CSCI508. ADVANCED TOPICS IN PERCEPTION AND COMPUTER VISION. 3.0 Semester Hrs.**

Equivalent with EENG508,
(II) This course covers advanced topics in perception and computer vision, emphasizing research advances in the field. The course focuses on structure and motion estimation, general object detection and recognition, and tracking. Projects will be emphasized, using popular software tools. Prerequisites: EENG507 or CSCI507. 3 hours lecture; 3 semester hours.

**Course Learning Outcomes**

- 1. Be able to review the literature on computer vision and create a critical review
- 2. Be able to design, develop, and evaluate algorithms for specific applications
- 3. Be able to use software tools to implement computer vision algorithms
- 4. Communicate (in oral and written form) methods and results to a technical audience

**CSCI520. SOFTWARE ENGINEERING SYSTEMS DEVELOPMENT I. 3.0 Semester Hrs.**

This is the first course of the two-semester sequence. In this course you will be addressing realistic, open-ended design changes for clients in interdisciplinary (when appropriate) teams. The design projects are chosen by the course faculty to develop creativity, encourage use of appropriate design methods and application of technical skills. You are expected to successfully address the given challenge. The devised solution in partnership with the client must be within the constraints of elements such as cost, sustainability, manufacturability/deployment. Projects many be both hardware and software focused. By the end of the first semester, teams should have a fully defined the system architecture, specifications, and operation. Solution components have been modeled, analyzed and selected and a proof-of-concept protype developed to demonstrate the solution to the client.

**Course Learning Outcomes**

- Develop and maintain a project management plan to address a software engineering design challenge that includes a clear definition of done and detailed project schedule.
- Formulate a clear, concise set of correctly constructed engineering metrics/constraints and specifications for a software/hardware engineering design challenge.
- Develop and graphically communicate multiple innovative high-level design solutions to a given software/hardware engineering challenge.
- Utilize decision methods to select the most promising solutions(s) that meet(s) constraints and requirements for the given design challenge.
- Develop a proof-of-concept protype(s) for the critical and high-risk functional elements of the design challenge.
- Develop a project completion plan and execute Agile project development methodology that allows the team to successfully meet the project goals.
- Apply appropriate technical knowledge to solve a design challenge.
- Communicate your engineering design, research, analysis, decision making and solution via professional, technical, and industry appropriate written documentation packages.
- Communicate technical information verbally as part of a sprint or design review and synthesize feedback from stakeholders and clients.
- Identify and analyze the ethical, environmental, societal and/or economic impact of considered design solutions.
- Function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks and meet design challenge objectives.
- Evaluate your success as a designer by reflecting on your experience and proposing strategies for future self-improvement.

**CSCI521. SOFTWARE ENGINEERING SYSTEMS DEVELOPMENT II. 3.0 Semester Hrs.**

This is the second course of the two-semester sequence. In this course you will be addressing realistic, open-ended design changes for clients in interdisciplinary (when appropriate) teams. The design projects are chosen by the course faculty to develop creativity, encourage use of appropriate design methods and application of technical skills. You are expected to successfully address the given challenge. The devised solution in partnership with the client must be within the constraints of elements such as cost, sustainability, manufacturability/deployment. Projects many be both hardware and software focused. By the end of the first semester, teams should have a fully defined the system architecture, specifications, and operation. Solution components have been modeled, analyzed and selected and a proof-of-concept prototype developed to demonstrate the solution to the client. Prerequisites: CSCI520.

**Course Learning Outcomes**

- Design an engineering solution for your given design challenge within constraints.
- Demonstrate design feasibility through engineering analysis.
- Identify project and/or technical risks and develop a proactive risk mitigation plan.
- Test and analyze a solution.
- Deploy a solution into the environment within constraints.
- Develop a project completion plan and execute Agile project development methodology that allows the team to successfully meet the project goals.
- Apply appropriate technical knowledge to solve a design challenge.
- Communicate your engineering design, research, analysis, decision making and solution via professional, technical, and industry appropriate written documentation packages.
- Communicate technical information verbally as part of a sprint or design review and synthesize feedback from stakeholders and clients.

- Identify and analyze the ethical, environmental, societal and/or economic impact of considered design solutions.
- Function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks and meet design challenge objectives.
- Evaluate your success as a designer by reflecting on your experience and proposing strategies for future self-improvement.

**CSCI532. ROBOT ETHICS. 3.0 Semester Hrs.**
(II) This course explores ethical issues arising in robotics and human-robot interaction through philosophical analysis, scientific experimentation, and algorithm design. Topics include case studies in lethal autonomous weapon systems, autonomous cars, and social robots, as well as higher-level concerns including economics, law, policy, and discrimination. Graduate enrollees will additionally participate in and report on the results of empirical and computational robot ethics research, with the goal of developing publishable works. Prerequisite: Graduate student standing.
**Course Learning Outcomes**

- 1 - Understand the basic ethical theories, concepts, tools, and frameworks for analyzing the social and ethical ramifications of robotics
- 2 - Be able to critically examine the ethical significance of the use of robotics in daily and technical fields including human-robot interaction, medicine, relationship, military, etc.
- 3 - Develop a critical attitude toward the role of robotics in shaping human society including human perceptions and behaviors
- 4 - Be able to use the theories, concepts, tools, and frameworks learned from this class to critically examine emerging robot ethics issues in the society.
- 5 - Understand the tradeoffs underlying the design of autonomous moral agents.
- 6 - Conduct robot ethics research grounded in both human-subject experimentation and algorithm development.

**CSCI534. ROBOT PLANNING AND MANIPULATION. 3.0 Semester Hrs.**
An introduction to planning in the context of robotics covering symbolic and motion planning approaches. Symbolic computation, symbolic domains, and efficient algorithms for symbolic planning; Robot kinematics, configuration spaces, and algorithms for motion planning. Applications of planning will focus on manipulation problems using robot arms.
**Course Learning Outcomes**

- 1 - Implement algorithms for symbolic computation
- 2 - Construct symbolic planning domains for new scenarios
- 3 - Implement algorithms for symbolic planning via constraint-solving and heuristic search
- 4 - Implement algorithms for sampling-based motion planning
- 5 - Construct kinematic models of robot manipulators
- 6 - Analyze planning algorithms for key properties: correctness, completeness, optimality
- 7 - Evaluate the suitability of different planning approaches and apply appropriate algorithms to new planning scenarios
- 8 - Communicate implementations, analysis, and evaluation in written and oral form

**CSCI536. HUMAN-ROBOT INTERACTION. 3.0 Semester Hrs.**
Human-Robot Interaction is an interdisciplinary field at the intersection of Computer Science, Robotics, Psychology, and Human Factors, that seeks to answer a broad set of questions about robots designed to interact with humans (e.g., assistive robots, educational robots, and service robots), such as: (1) How does human interaction with robots differ from interaction with other people? (2) How does the appearance and behavior of a robot change how humans perceive, trust, and interact with that robot? And (3) How can we design and program robots that are natural, trustworthy, and effective? Accordingly, In this course, students will learn (1) how to design interactive robots, (2) the algorithmic foundations of interactive robots; and (3) how to evaluate interactive robots. To achieve these learning objectives, students will read and present key papers from the HRI literature, complete an individual final project tailored to their unique interests and skillsets, and complete a group project in which they will design, pilot, and evaluate novel HRI experiments, with in-class time expected to be split between lecture by the instructor, presentations by students, and either collaborative active learning activities or discussions with researchers in the field. Prerequisite: Data Structures, Probability and Statistics or equivalent.
**Course Learning Outcomes**

- Understand the theoretical foundations and critical application domains of human-robot interaction.
- Employ design techniques to design interactive robots.
- Design human-subject experiments to evaluate interactive robots.
- Perform qualitative and quantitative analysis on the results of human-robot interaction experiments.

**CSCI538. AUGMENTED REALITY. 3.0 Semester Hrs.**
Augmented reality is the process of augmenting the real world with virtual content, typically with hand-held or head-mounted displays. This course will provide an overview of augmented reality, including applications, technical foundations (computer vision, optics, graphics, and human factors), and recent developments in the field. Projects will be emphasized, using popular software tools. Augmented reality is a systems-thinking problem where it is helpful to have a good understanding of several areas, including computer vision, optics, graphics, and human-computer interaction. Projects will provide students with opportunities to gain a deeper understanding of these areas, as well as to build a portfolio for possible future careers in augmented reality.
**Course Learning Outcomes**

- At the completion of the course, you will be able to:

**CSCI542. SIMULATION. 3.0 Semester Hrs.**
(I) Advanced study of computational and mathematical techniques for modeling, simulating, and analyzing the performance of various systems. Simulation permits the evaluation of performance prior to the implementation of a system; it permits the comparison of various operational alternatives without perturbing the real system. Topics to be covered include simulation techniques, random number generation, Monte Carlo simulations, discrete and continuous stochastic models, and point/interval estimation. Offered every other year. 3 hours lecture; 3 semester hours.

**CSCI544. ADVANCED COMPUTER GRAPHICS. 3.0 Semester Hrs.**
Equivalent with MATH544,
This is an advanced computer graphics course in which students will learn a
variety of mathematical and algorithmic techniques that can be used to solve

fundamental problems in computer graphics. Topics include global illumination,
GPU programming, geometry acquisition and processing, point based graphics
and non-photorealistic rendering. Students will learn about modern rendering and
geometric modeling techniques by reading and discussing research papers and
implementing one or more of the algorithms described in the literature.

**CSCI555. GAME THEORY AND NETWORKS. 3.0 Semester Hrs.**
Equivalent with CSCI455,
(II) An introduction to fundamental concepts of game theory with a focus on the applications in networks. Game theory is the study that analyzes the strategic interactions among autonomous decision-makers. Originated from economics. Influenced many areas in Computer Science, including artificial intelligence, e-commerce, theory, and security and privacy. Provides tools and knowledge for modeling and analyzing real-world problems. Prerequisites: CSCI406 Algorithms. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- 1. Understand the basic concepts in game theory
- 2. Be able to model and analyze real-world problems as games
- 3. Learn about the game theoretic applications in networks
- 4. Have the opportunity to apply game theory to other fields

**CSCI560. FUNDAMENTALS OF COMPUTER NETWORKS. 3.0 Semester Hrs.**
This fully online course provides an introduction to fundamental concepts in the design and implementation of computer communication networks, their protocols, and applications. Topics include overview of network architectures, applications, network programming interfaces (e.g., sockets), transport, congestion, routing, and data link protocols, addressing, local area networks, wireless networks, and network security. Examples are drawn primarily from the Internet (e.g., TCP, UDP, and IP) protocol suite. If you have taken CSCI 471, you will not receive credit for this course. Prerequisite: CSCI442.
**Course Learning Outcomes**

- 1) Explain how packet switching works
- 2) Compute and identify potential packet delays in a packet-switched network when provided specific parameters of network conditions.
- 3) Articulate in laymen's terms the following concepts or processes: a) essential principles of a transport layer protocol (reliable data transfer, flow control, congestion control), b) data link layer services and multiple access techniques, c) how mobility is managed in cellular networks, and d) network security issues and provide examples of a few methods that address them
- 4) Apply routing algorithms to find shortest paths for network-layer packet delivery
- 4) Apply routing algorithms to find shortest paths for network-layer packet delivery
- 5) Apply Wireshark, a network sniffing tool, to observe and analyze behaviors of the networking protocols studied in this course
- 6) Design and implement distributed applications using the socket APIs and support for TCP/UDP communications between end hosts

**CSCI561. THEORY OF COMPUTATION. 3.0 Semester Hrs.**
(I) An introduction to abstract models of computation and computability theory; including finite automata (finite state machines), pushdown automata, and Turing machines. Language models, including formal languages, regular expressions, and grammars. Decidability and undecidability of computational problems. 3 hours lecture; 3 semester hours. Prerequisite: CSCI406.
**Course Learning Outcomes**

- Design and implement various types of automata, including finite automata, pushdown automata, and Turing machines.
- Model and solve computational problems using formal language representations and algorithms.
- Communicate effectively using mathematically precise terminology, particularly about topics in language and complexity theory.
- Formally prove capabilities and limits, such as decidability and complexity of new problems, based on computational classes.
- Evaluate potentially effective (or ineffective) approaches for new problems based on language and complexity class.
- Apply reduction techniques to show the equivalence between different computational problems.

**CSCI562. APPLIED ALGORITHMS AND DATA STRUCTURES. 3.0 Semester Hrs.**
(II) Industry competitiveness in certain areas is often based on the use of better algorithms and data structures. The objective of this class is to survey some interesting application areas and to understand the core algorithms and data structures that support these applications. Application areas could change with each offering of the class, but would include some of the following: VLSI design automation, computational biology, mobile computing, computer security, data compression, web search engines, geographical information systems. 3 hours lecture; 3 semester hours. Prerequisite: CSCI406.
**Course Learning Outcomes**

- Communicate effectively on matters related to algorithms and data structures to a range of audiences using a range of media.
- Solve moderately open-ended problems related to graphs, NP completeness, approximation algorithms, and geometric algorithms.
- Demonstrate attention to detail (with respect to definitions, terminology, notation, language) as measured by performance on multiple-choice and true-false questions on online-quizzes.
- Execute a sequence of increasingly difficult (but guided) research related tasks related to an important application area that requires.
- Function effectively as a team member with effectiveness being determined by peer ratings, self-assessment and instructor observations.

**CSCI563. PARALLEL COMPUTING FOR SCIENTISTS AND ENGINEERS. 3.0 Semester Hrs.**
(I) Students are taught how to use parallel computing to solve complex scientific problems. They learn how to develop parallel programs, how to analyze their performance, and how to optimize program performance. The course covers the classification of parallel computers, shared memory versus distributed memory machines, software issues, and hardware issues in parallel computing. Students write programs for state of the art high performance supercomputers, which are accessed over the network. Prerequisite: Programming experience in C. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Develop parallel programs to solve complex scientific problems using both shared memory and distributed memory models.

- Analyze and optimize the performance of parallel algorithms to achieve efficient computational solutions.
- Classify and differentiate between various parallel computing architectures and understand the associated hardware and software challenges.
- Gain hands-on experience with high-performance supercomputers by writing, testing, and debugging parallel applications over networked environments.

**CSCI564. ADVANCED COMPUTER ARCHITECTURE. 3.0 Semester Hrs.**
The objective of this class is to gain a detailed understanding about the options available to a computer architect when designing a computer system along with quantitative justifications for the options. All aspects of modern computer architectures including instruction sets, processor design, memory system design, storage system design, multiprocessors, and software approaches will be discussed. Prerequisite: CSCI341. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Understand quantitative methods to evaluate system performance, including metrics and benchmarks.
- Analyze the design and optimization of memory hierarchies, including caches and virtual memory.
- Understand CPU pipelines, focusing on throughput and instruction scheduling.
- Understand the techniques for speculative execution and branch prediction.
- Understand the GPU architecture.

**CSCI565. DISTRIBUTED SYSTEMS. 3.0 Semester Hrs.**
This course discusses concepts, techniques, and issues in developing distributed systems in large scale networked environment. Topics include theory and systems level issues in the design and implementation of distributed systems.
**Course Learning Outcomes**

- Analyze complexity of distributed algorithms.
- Prove correctness of distributed algorithms.
- Implement virtual clocks.
- Implement and evaluate distributed minimum spanning tree algorithms.
- Implement distributed mutual exclusion algorithms.
- Compare and contrast distributed leader election algorithms.
- Implement different data-centric and client-centric consistency models.
- Review recent distributed systems research.

**CSCI568. DATA MINING. 3.0 Semester Hrs.**
This course is an introductory course in data mining. It covers fundamentals of data mining theories and techniques. We will discuss association rule mining and its applications, overview of classification and clustering, data preprocessing, and several application specific data mining tasks. We will also discuss practical data mining using a data mining software. Project assignments include implementation of existing data mining algorithms, data mining with or without data mining software, and study of data mining related research issues. 3 hours lecture; 3 semester hours.

**CSCI571. ARTIFICIAL INTELLIGENCE. 3.0 Semester Hrs.**
Artificial Intelligence (AI) is the subfield of computer science that studies how to automate tasks for which people currently exhibit superior performance over computers. Historically, AI has studied problems such as machine learning, language understanding, game playing, planning, robotics, and machine vision. AI techniques include those for uncertainty management, automated theorem proving, heuristic search, neural networks, and simulation of expert performance in specialized domains like medical diagnosis. This course provides an overview of the field of Artificial Intelligence. Particular attention will be paid to learning the LISP language for AI programming. Prerequisite: CSCI262.

**CSCI572. COMPUTER NETWORKS II. 3.0 Semester Hrs.**
This course explores how computer networking is evolving to support new environments, and challenges in building networked systems that are simultaneously highly robust, efficient, flexible, and secure. Detailed topics include wireless and mobile networks, multimedia networking, and network security. In addition, recent research and developments are also studied, which include mobile sensing, Internet of Things (IoT), social computing and networks, mobile ad-hoc networks, wireless sensor networks, software defined networking, and future Internet architecture.
**Course Learning Outcomes**

- Articulate wireless networking challenges.
- Describe wireless MAC layer protocols.
- Describe the design of WiFi networks and Cellular networks.
- Use network sniffing tools to characterize the impact of physical environments on wireless signal propagation.
- Use a network simulator to evaluate the performance of routing protocols for wireless ad-hoc networks.
- Analyze WiFi's MAC layer protocol in different scenarios using a network simulator.
- Review recent wireless networking research.

**CSCI573. ROBOT PROGRAMMING AND PERCEPTION. 3.0 Semester Hrs.**
Equivalent with CSCI473,
In this class students will learn the basics of integrated robot system programming and the design and use of algorithms for robot perception. Students will learn how to use the ROS robot middleware for the design of robot systems for perceiving and navigating the world; develop reinforcement learning based models for perception-informed autonomous navigation; and develop computational models for 3D robot perception and perceptual representation of human data.
**Course Learning Outcomes**

- 1. Explain the basic concepts in human-centered robotics
- 2. Model and analyze human behaviors for human-robot interaction applications
- 3. Recognize the cutting-edge human-centered robotics reasearch and applications
- 4. Apply the learned knowledge to other fields

**CSCI574. THEORY OF CRYPTOGRAPHY. 3.0 Semester Hrs.**
Equivalent with MATH574,
(I) Students will draw upon current research results to design, implement and analyze their own computer security or other related cryptography projects. The requisite mathematical background, including relevant aspects of number theory and mathematical statistics, will be covered in lecture. Students will be expected to review current literature from prominent researchers in cryptography and to present their findings

to the class. Particular focus will be given to the application of various techniques to real-life situations. The course will also cover the following aspects of cryptography: symmetric and asymmetric encryption, computational number theory, quantum encryption, RSA and discrete log systems, SHA, steganography, chaotic and pseudo-random sequences, message authentication, digital signatures, key distribution and key management, and block ciphers. Prerequisite: CSCI262. 3 hours lecture, 3 semester hours.

**Course Learning Outcomes**

- Explain the basic terms and concepts in cryptography.
- Correlate number theory with cryptography.
- Analyze the limitations of classical cryptographic algorithms.
- Compare the similarities and differences between symmetric and asymmetric encryption algorithms.
- Assess the security strength of cryptographic techniques.
- Choose appropriate cryptographic techniques such as hashing, message authentication, and digital signature for addressing real-world security and privacy problems.
- Critique research work in applied cryptography.

**CSCI575. ADVANCED MACHINE LEARNING. 3.0 Semester Hrs.**

Machine learning is the study of computer algorithms that improve automatically through experience. Machine learning systems do not have to be programmed by humans to solve a problem; instead, they essentially program themselves based on examples of how they should behave, or based on trial and error experience trying to solve the problem. This course aims at provide students with an understanding of the capabilities of machine learning (especially for deep learning due to its state-of-the-art performance for predicting and understanding data), and the knowledge to formulate the real-world problem to solve it effectively by a combination of computational idea motivations, learning theories, mathematical and optimization backgrounds/tools. Prerequisite: CSCI470.

**Course Learning Outcomes**

- Understand the different types of machine learning and some popular methods in each.
- Be able to use machine learning methods in real-world applications.
- Be able to determine applicable machine learning techniques for different datasets.
- Understand how to use machine learning to learn features from high dimensional or complex data.
- Understand the ethical implications of machine learning models.

**CSCI576. DEEP LEARNING. 3.0 Semester Hrs.**

Machine Learning is a key component of Artificial Intelligence that allows computers to generate accurate outcomes without being explicitly programmed. Over the past decade, machine learning has powered speech recognition, augmented reality, self-driving vehicles, and biometric authentications. The purpose of this course is to bridge general machine learning concepts to real world applications. This course provides a broad introduction to machine learning (supervised learning, unsupervised learning, feature learning), deep learning, computer vision, natural language processing, and reinforcement learning. During the course, students will design a project that applies concepts from class to several diGerent real-world problems and challenges and create applications to solve them. Prerequisite: CSCI470.

**Course Learning Outcomes**

- Apply supervised, unsupervised, reinforcement machine learning models and deep learning models to solve problems in areas such as prediction, recognition and classification.
- Explore and develop with various tools, techniques and libraries in Python for data processing, feature extraction, visualization, validation and evaluation.
- Create data visualization tools, techniques, and libraries in Python to visualize high dimensional or complex data for stakeholders
- Determine ethical implications through interpretability of big data and results from the application of various machine learning models
- Design and develop a machine learning product that solves their chosen real-world challenge
- Create a video presentation that succinctly outlines the problem, solutions, conclusions, and lessons learned regarding product development for the stakeholders

**CSCI577. ADVANCED ELEMENTS OF GAMES AND GAME DEVELOPMENT. 3.0 Semester Hrs.**

This course provides an overview of computer and video game development along with practical game projects designed to introduce the student to the computer entertainment industry. Topics will include the nature of games, the game player, game play, game design, game mechanics, story and character, game worlds, interface and the game development process. Students will be required to develop code in existing game engines (GameMaker, Unity, and Unreal). Students will also work on a game engine from scratch, using a hybrid software design pattern that is an object-oriented hierarchy with components. The majority of the course will be dedicated to a semester-long game project where students will create a complete game with a teammate using Agile principles, a backlog, a design document, demos, and a final product with commercial video. Prerequisite: CSCI 306.

**Course Learning Outcomes**

**CSCI578. BIOINFORMATICS. 3.0 Semester Hrs.**

This course contains 4 main modules organized around different data types produced by biotechnological assays, i.e., DNA/protein sequences, protein structures, gene activity levels, relationships between biological entities. Students will have a chance to interact with different public datasets and experiment with different tools and platforms with hands-on exercises. The main objective of the course is to provide the student with a solid foundation for conducting further research in bioinformatics. By the end of the course, the students will have learned: the bioinformatics terminology, main bioinformatics problems, and the key computational methods and tools used in bioinformatics. Prerequisites: Prior experience with introductory programming concepts.

**Course Learning Outcomes**

- Construct a systems level abstraction of the dynamics of a cell by relating components of the cell such as genes, proteins, and metabolic reactions
- Design and implement algorithms for solving pairwise, multiple sequence alignments, and search sequence databases using sequences from NCBI GenBank or Uniprot
- Design and implement algorithms for constructing phylogenetic trees for a set of biological sequences and apply them on real datasets on sequence families, such as SARS-CoV-2 variants
- Apply existing tools to predict protein structures from sequence and compare multiple protein structures using sequences from Uniprot and structures from the Protein Data Bank

- Interpret and analyze transcriptome data such as microarray data or RNA-Seq data by to reveal clusters of genes/samples and identify differentially expressed genes
- Design and implement algorithms for analyzing biological networks such as protein-protein interaction networks, gene-regulatory networks, and metabolic networks

**CSCI580. ADVANCED HIGH PERFORMANCE COMPUTING. 3.0 Semester Hrs.**
This course provides students with knowledge of the fundamental concepts of high performance computing as well as hands-on experience with the core technology in the field. The objective of this class is to understand how to achieve high performance on a wide range of computational platforms. Topics will include sequential computers including memory hierarchies, shared memory computers and multicore, distributed memory computers, graphical processing units (GPUs), cloud and grid computing, threads, OpenMP, message passing (MPI), CUDA (for GPUs), parallel file systems, and scientific applications. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Develop skills to design, implement, and debug parallel programs using frameworks like MPI and OpenMP.
- Learn to analyze and optimize computational performance on multi-core and distributed systems.
- Understand and apply algorithms that efficiently scale across high-performance computing architectures.
- Gain familiarity with HPC tools, libraries, and systems to solve complex computational problems effectively.

**CSCI581. QUANTUM PROGRAMMING. 3.0 Semester Hrs.**
This course serves as an introduction to programming quantum computers. Students will receive an in depth education in quantum algorithms and their design, and then break into teams to learn the API of a commercially available quantum computing system. They will use this system to write and test simple quantum algorithms, and debug their code to improve its performance against noise and other error sources. Prerequisite: PHGN519.
**Course Learning Outcomes**

- Building on the education received in Fundamentals of Quantum Information, students will learn:
- 1. How to write and implement simple quantum algorithms,
- 2. Understand mechanisms by which a quantum speedup can be obtained
- 3. Use and execute code on an API of publicly available quantum hardware (e.g. IBM's qiskit, Rigetti's Forest, Google's forthcoming Cirq, and many more)
- 4. "Debug" their code to improve its performance given the realities of noise and gate error

**CSCI582. COMPUTING BEYOND CPU'S. 3.0 Semester Hrs.**
CPUs are no longer fast enough to execute demanding tasks in emerging domains such as artificial intelligence, robotics and mobile computing. Most modern systems come with specialized, i.e., "beyond the CPU", processing units such as GPUs, neural network processors, and other domain-specific accelerators. This class will provide students with knowledge and hands-on experience with accelerators. We will dig deep into the world of specialized computing and: (a) teach students the fundamental computer architecture concepts that lead to the development of accelerators, (b) let the students know about modern accelerators, their internal architectures, and how to program them to solve many prevalent computational problems in an energy and performance efficient way, and (c) provide students a hands-on experience by implementing and running benchmarks on an accelerator of their choice and perform a detailed performance analysis. The course assignments will include weekly paper reading, mini programming assignments, paper presentations (one or two times in the semester) and a semester project that will be carried out on an accelerator of student's choice. The students will be given access to a diverse range of modern heterogeneous processing units that are designed to accelerate mobile, cloud and autonomous workloads. Prerequisite: CSCI 341.
**Course Learning Outcomes**

- Explore the principal design concepts of domain-specific accelerators, contrast them to traditional CPU architectures, understand how they are programmed, and comprehend their role and importance in modern computing.
- Improve critical thinking and analysis abilities on accelerated computing research and practice technical presentation of concepts and papers in both spoken and written forms.
- Measure and analyze performance of the state-of-the-art system-on-chips for autonomous and mobile computing using industry-standard parallel-programming languages, paradigms, and APIs.

**CSCI583. IOT SECURITY AND PRIVACY. 3.0 Semester Hrs.**
The use of IoT (Internet-of-Things) devices in U.S. homes is becoming increasingly popular. These smart devices, however, come with a range of security and privacy risks that need to be addressed. This course focuses on teaching the basics and advanced concepts of IoT security and privacy from a data-driven perspective. It covers topics such as networking and Internet security, as well as security research based on data analysis. Students will be required to read and present academic papers from various disciplines such as computer science, psychology, policy, and law. The course also includes hands-on projects that allow students to independently investigate real-world security and privacy issues of IoT devices and suggest practical solutions to fix them. Through this course, students will develop a comprehensive understanding of the security and privacy challenges posed by IoT devices and learn how to approach these issues in a data-driven and evidence-based manner.
**Course Learning Outcomes**

- Develop a comprehensive understanding of the security and privacy challenges posed by IoT devices.
- Approach these issues in a data-driven and evidence-based manner.
- Read, understand, present, and critique IoT academic papers.
- Analyze, formulate and address IoT security and privacy research problems.
- Master cutting-edge IoT data analysis techniques using AI models (e.g., generative and embedded AI).

**CSCI585. INFORMATION SECURITY PRIVACY. 3.0 Semester Hrs.**
This course provides an introduction to the principles and best practices in information security and privacy. Lectures will include basic concepts of information security and privacy, fundamental security design principles, major topics in security and privacy, essential knowledge and skills, risk assessment and mitigation, policy development, and so on. In the classroom, students will also present and discuss a list of recent or classic research papers corresponding to the major topics in security and privacy. Outside of the classroom, students will work on homework assignments, security lab exercises, quizzes, research paper summaries, and a course project. Prerequisite: (CSCI262 or CSCI220) and CSCI341.

**Course Learning Outcomes**

- Explain the fundamental security and privacy protection principles, techniques, and practices.
- Describe risk mitigation, legal requirements, and ethical considerations in cybersecurity.
- Analyze real-world security and privacy problems in modern computing environments.
- Practice security and privacy protection tools and techniques.
- Critique existing security and privacy protection techniques or studies.

**CSCI587. CYBER PHYSICAL SYSTEMS SECURITY. 3.0 Semester Hrs.**
(II) This course aims to build a solid foundation for students to identify, analyze, and evaluate real-world security and privacy problems in Cyber Physical Systems, as well as to design and develop secure and usable solutions for addressing these problems. It focuses on the important security and privacy research topics in representative Cyber Physical Systems such as wireless sensor networks, smart grids, autonomous automotive systems, and robotic systems. It also includes the discussion of the protection of the nation's critical infrastructures such as Food, Health, Water, Energy, Finance, Communication, Manufacturing, Government, and Transportation. The format of the course includes introductory discussions, research paper reading, summaries, and discussions, as well as research projects. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- 1. Students will be able to explain the essential security and privacy protection requirements in representative Cyber Physical Systems.
- 2. Students will be able to analyze security and privacy problems in representative Cyber Physical Systems.
- 3. Students will be able to analyze and evaluate research articles in Cyber Physical Systems security and privacy protection.
- 4. Students will be able to design usable solutions for addressing security and privacy problems in representative Cyber Physical Systems.

**CSCI597. SUMMER PROGRAMS. 0-6 Semester Hr.**

**CSCI598. SPECIAL TOPICS. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**CSCI598. SPECIAL TOPICS. 0-6 Semester Hr.**

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**CSCI599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**CSCI599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

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**CSCI691. GRADUATE SEMINAR. 1.0 Semester Hr.**
Presentation of latest research results by guest lecturers, staff, and advanced students. Prerequisite: none. 1 hour seminar; 1 semester hour. Repeatable for credit to a maximum of 12 hours.

**CSCI698. SPECIAL TOPICS. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**CSCI699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience

and maximums vary by department. Contact the Department for credit limits toward the degree.

**CSCI700. MASTERS PROJECT CREDITS. 1-6 Semester Hr.**
(I, II, S) Project credit hours required for completion of the non-thesis Master of Science degree in Computer Science (Project Option). Project under the direct supervision of a faculty advisor. Credit is not transferable to any 400, 500, or 600 level courses. Repeatable for credit.

**CSCI707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.**
(I, II, S) GRADUATE THESIS/DISSERTATION RESEARCH CREDIT Research credit hours required for completion of a Masters-level thesis or Doctoral dissertation. Research must be carried out under the direct supervision of the student's faculty advisor. Variable class and semester hours. Repeatable for credit.

## Professor and Department Head

Iris Bahar

## Professors

Qi Han

Dinesh Mehta

## Associate Professors

Hua Wang

Bo Wu

Thomas Williams

Dejun Yang

Chuan Yue

## Assistant Professors

Mehmet Belviranli

Dong Chen

Neil Dantam

Gabriel Fierro

C. Estelle Smith

## Teaching Professors

Tolga Can

Vibhuti Dave

Jeffrey Paone

Christopher Painter-Wakefield

## Teaching Associate Professors

Wendy Fisher, Assistant Department Head

Kathleen Kelly

## Teaching Assistant Professors

Amelia Read

Robert Thompson

Zibo Wang

## Professors of Practice

Mark Baldwin

Phil Romig

## Visiting Teaching Associate Professor

Keith Hellman

## Emeriti Professors

Tracy Camp , Emeritus Professor

William Hoff, Emeritus Associate Professor

Cyndi Rader, Emeritus Teaching Professor

# Economics and Business

## Degrees Offered

- Master of Science (Mineral and Energy Economics)
- Doctor of Philosophy (Mineral and Energy Economics)
- Master of Science (Engineering and Technology Management)
- Graduate Certificate in Resource Commodity Analytics (RCA)
- Graduate Certificate in Business Analytics
- Graduate Certificate in Product Management

## Mineral and Energy Economics Program Description

In an increasingly global and technical world, government and industry leaders in the mineral and energy areas require a strong foundation in economic and business skills. The department offers such skills in unique programs leading to MS and PhD degrees in Mineral and Energy Economics. Course work and research emphasizes the use of models to aid in decision making. Beyond the core courses students in the Mineral and Energy Economics Program may select, in consultation with their advisor from a set of electives that fit their specialized needs and educational goals.  This may include advanced courses in applied economics, finance, and operations research.

## Engineering and Technology Management Program Description

The department also offers an MS degree in Engineering and Technology Management (ETM). The ETM degree program is designed to integrate the technical elements of engineering practice with the managerial perspective of modern engineering and technology management. A major focus is on the business and management principles related to this integration. The ETM Program provides the analytical tools and managerial perspective needed to effectively function in a highly competitive and technologically complex business economy.

Students in the ETM Program may select elective courses from two areas of focus:  Engineering Management and Optimization or Technology Management and Innovation. The Optimization courses focus on developing knowledge of advanced operations research, optimization, and decision-making techniques applicable to a wide array of business and engineering problems.  The engineering management courses

emphasize valuable techniques for managing large engineering and technical projects effectively and efficiently. The strategy and innovation courses teach the correct match between organizational strategies and structures to maximize the competitive power of technology with a particular emphasis on management issues associated with the modern business enterprise.

## Combined Degree Program Option

Mines undergraduate students have the opportunity to begin work on a MS degree in Mineral and Energy Economics or Engineering and Technology Management while completing their bachelor's degree at Mines. For more information please contact the EB Office or visit https://econbus.mines.edu/.

## Graduate Certificate in Resource Commodity Analytics

The Mines graduate certificate in Resource Commodity Analytics (RCA) is a four-course program that provides training in advanced quantitative and financial analysis applied to energy and mineral industries. The RCA certificate program takes the most quantitative aspects of our world-renowned graduate programs in Mineral and Energy Economics, and Engineering and Technology Management, and distills them into an accelerated certificate. This program is designed for professionals and recent graduates who want to acquire new skills for career advancement or get a head start on a graduate degree. Courses in the program focus on natural resource markets and regulation, data analysis and forecasting, and financial valuation. The course of study is flexible enough to be completed in one intensive semester or over four semesters depending on the student's needs and interests.

In an increasingly global and technical world, government and industry leaders in the mineral and energy areas require a strong foundation in economic and business skills. The division offers such skills in unique programs leading to MS and PhD degrees in Mineral and Energy Economics. Course work and research emphasizes the use of models to aid in decision making. Beyond the core courses in the Mineral and Energy Economics Program, students may select, in consultation with their advisor, from a set of electives that fit their specialized needs and educational goals. This may include advanced courses in Applied Economics, Finance, and Operations Research.

The division offers the following programs whose requirements are specified on this page:

1. MS in Mineral and Energy Economics
2. PhD in Mineral and Energy Economics
3. Mines' Combined Undergraduate/Graduate Degree Program
4. Colorado Mesa University Combined Undergraduate/Graduate Degree Program
5. Western Colorado University Combined Undergraduate/Graduate Degree Program
6. IFP School Dual Degree Program

## I. MS in Mineral and Energy Economics Program Requirements

**MS Degree** Students choose from either the thesis or non-thesis option in the master of science (MS) program and are required to complete a minimum total of 36 credits (a typical course has 3 credits). Initial admission is only to the non-thesis program. Admission to the thesis option requires subsequent application after at least one full-time equivalent semester in the program.

| **Non-thesis option** | |
|---|---|
| Core courses | 15.0 |
| Approved electives* | 21.0 |
| **Total Semester Hrs** | **36.0** |

| **Thesis option** | |
|---|---|
| Core courses | 15.0 |
| Research credits | 12.0 |
| Approved electives* | 9.0 |
| **Total Semester Hrs** | **36.0** |

* Non-thesis MS students may apply six elective credits toward a nine hour minor in another department. See below for details.

**Further Degree Requirements**

All thesis and non-thesis students in the Mineral and Energy Economics Program are required to attend the Distinguished Lecture Series sponsored by the Payne Institute for Earth Resources and the Division of Economics and Business. This series facilitates active involvement in the Mineral and Energy Economics Program by top researchers and influential leaders in the policy arena. The program director will outline attendance requirements at the beginning of each fall semester.

**Required Course Curriculum**

All MS students in Mineral and Energy Economics are required to take a set of core courses that provide basic tools for the more advanced and specialized courses in the program.

**a. Core Courses**

| | | |
|---|---|---|
| EBGN509 | MATHEMATICAL ECONOMICS | 3.0 |
| EBGN510 | NATURAL RESOURCE ECONOMICS | 3.0 |
| EBGN521 | MICROECONOMICS OF MINERAL AND ENERGY MARKETS | 3.0 |
| EBGN590 | ECONOMETRICS I | 3.0 |
| EBGN594 | TIME-SERIES ECONOMETRICS An alternative econometrics elective may be substituted for EBGN594 | 3.0 |
| **Total Semester Hrs** | | **15.0** |

**b. Approved Electives (21 credits for MS non-thesis option or 9 credits for MS thesis option)**

All EBGN graduate courses are approved electives. Other courses outside of Economics and Business can be counted with advisor and program director approval.

## Prerequisites for the Mineral and Energy Economics Programs

Students must have completed the following undergraduate prerequisite courses prior to beginning the program with a grade of B or better:

1. Principles of Microeconomics;
2. One semester of college-level Calculus;
3. Probability and Statistics

## Minor from Another Department

Non-thesis MS students may apply six elective credits towards a 9-hour minor in another department. A minor is ideal for those students who want to enhance or gain knowledge in another field while gaining the economic and business skills to help them move up the career ladder. For example, a petroleum, chemical, or mining engineer might want to learn more about environmental engineering, a geophysicist or geologist might want to learn the latest techniques in their profession, or an economic policy analyst might want to learn about political risk. Students should check with the minor department for the opportunities and requirements.

**Transfer Credits**

The student must have achieved a grade of B or better in all graduate transfer courses, and the transfer credit must be approved by the student's advisor and the Division Director. The total number of transfer credits allowed in the Mineral and Energy Economics program will follow Colorado School of Mines Graduate School rules.

## II. PhD in Mineral and Energy Economics Program Requirements

**PhD Degree** Doctoral students develop a customized curriculum to fit their needs. The degree requires a minimum of 72 graduate credits that includes course work and a thesis.

| **Course work (requires advisor and committee approval)** | |
|---|---|
| First year Core courses | 15.0 |
| Extended Core | 3.0 |
| Approved electives | 18.0 |
| **Total Semester Hrs** | **36.0** |

**Research credits**

| | |
|---|---|
| Research credits | 36.0 |

The student's faculty advisor and the doctoral thesis committee must approve the student's program of study and the topic for the thesis.

## Qualifying Examination Process

Upon completion of the first-year core coursework, PhD students must pass a first set of qualifying written examinations (collectively Qualifier 1). A student will receive one of four possible grades on the Micro Economics and Quantitative Methods examinations: high pass, pass, marginal fail, or fail. A student receiving a marginal fail on one or both of the examinations will have the opportunity to retake the relevant examination(s) within a year of the initial attempt. Students receiving a marginal fail should consult their advisor as to whether to retake exams during the winter or summer breaks. A student receiving a fail or consecutive marginal fails will be dismissed from the program. Consistent with university policy, the faculty will grade and inform students of qualification examination results within two weeks of the examinations.

Upon completion of the extended core (typically in the second year), PhD students must pass a second qualifying written examination (Qualifier II). A student will receive one of four possible grades on Qualifier II: high pass, pass, marginal fail, or fail. A student receiving a marginal fail on Qualifier II will have the opportunity to retake the exam or relevant portions of the exam as determined by the examination committee within a year of the initial attempt. Students receiving a marginal fail should consult their advisor as to whether to retake exams during the winter or summer breaks. A student receiving a Fail or consecutive Marginal Fails, on Qualifier II will be dismissed from the program. Consistent with university policy, the faculty will grade and inform students of qualification examination results within two weeks of the examinations.

Following a successful thesis-proposal defense and prior to the final thesis defense, a student is required to present a completed research paper (or dissertation chapter) in a research seminar at Mines. The research presentation must be considered satisfactory by at least three Mines faculty members in attendance.

**Required Course Curriculum**

All PhD students in Mineral and Energy Economics are required to take a set of core courses that provide basic tools for the more advanced and specialized courses in the program.

**a. Core Courses**

| | | |
|---|---|---|
| EBGN509 | MATHEMATICAL ECONOMICS | 3.0 |
| EBGN510 | NATURAL RESOURCE ECONOMICS | 3.0 |
| EBGN521 | MICROECONOMICS OF MINERAL AND ENERGY MARKETS | 3.0 |
| EBGN590 | ECONOMETRICS I | 3.0 |
| EBGN594 | TIME-SERIES ECONOMETRICS An alternative econometrics elective may be substituted for EBGN594 | 3.0 |
| **Total Semester Hrs** | | **15.0** |

**b. Extended Core Courses**

| | | |
|---|---|---|
| EBGN611 | ADVANCED MICROECONOMICS | 3.0 |
| **Total Semester Hrs** | | **3.0** |

**c. Approved Electives (18 credits)**

The student, in consultation with their advisor, will choose six additional courses. A minimum of two courses must be advanced economics courses. The program of study can be customized to fit the individual student's educational goals, but must be approved by their advisor.

## Prerequisites for the Mineral and Energy Economics Programs

Students must have completed the following undergraduate prerequisite courses prior to beginning the program with a grade of B or better:

1. Principles of Microeconomics
2. One semester of college-level Calculus
3. Probability and Statistics

## Minor from Another Department

PhD students for coursework may apply six elective credits towards a 9-hour minor in another department. A minor is ideal for those students who want to enhance or gain knowledge in another field while gaining the economic and business skills to help them move up the career ladder. For example, a petroleum, chemical, or mining engineer might want to learn more about environmental engineering, a geophysicist or geologist might want to learn the latest techniques in their profession, or an economic policy analyst might want to learn about political risk. Students should check with the minor department for the opportunities and requirements.

**Transfer Credits**

The student must have achieved a grade of B or better in all graduate transfer courses, and the transfer credit must be approved by the student's advisor and the Division Director. The total number of transfer credits allowed in the Mineral and Energy Economics program will follow Colorado School of Mines Graduate School rules.

**Unsatisfactory Progress**

In addition to the institutional guidelines for unsatisfactory progress as described elsewhere in this bulletin, unsatisfactory progress will be assigned to any full-time PhD student who does not pass the first-year core courses on time. EBGN509, EBGN510, and EBGN521 in the first fall semester of study and EBGN590 in the first spring semester of study. Unsatisfactory progress will also be assigned to any students who do not complete requirements as specified in their admission letter. Part-time students develop an approved course plan with their advisor.

PhD Students are expected to take the first set of qualification examinations (Qualifier I) in the first summer following eligibility. Unsatisfactory progress may be assigned to any student who does not meet this expectation. Consistent with university policy, consideration will be given to students who have documented illness or other qualifying personal events that prevent them from taking Qualifier I. A marginal fail on a qualification examination does not trigger the assignment of unsatisfactory progress. Unsatisfactory progress will, however, be assigned to a student who fails to retake a marginally failed examination in the next available summer offering.

## III Mines' Combined Undergraduate/Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to six credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

## Prerequisites for the Mineral and Energy Economics Programs

Students must have completed the following undergraduate prerequisite courses prior to beginning the program with a grade of B or better:

1. Principles of Microeconomics
2. One semester of college-level Calculus
3. Probability and Statistics

## IV. Colorado Mesa University Combined Undergraduate/Graduate Degree Program

Please see the Mines Registrar Transfer Agreements webpage for detailed information.

Colorado School of Mines shares a Memorandum of Understanding (MoU) with Colorado Mesa University. Through this program Colorado School of Mines (Mines) and Colorado Mesa University (CMU), jointly provide opportunity to transition CMU Bachelor of Business Administration Energy Management/Landman graduates to Mines in order to earn a MS Non-Thesis degree. This MoU grants students with the opportunity to apply up to six undergraduate-coursework credits applied to their from Colorado Mesa University degree toward their Mines graduate-degree requirements, while also waived graduate admissions application fee, waived requirement for three letters of recommendation, and exemption from submitting GRE test scores.

CMU students who successfully pass courses and meet the admission criteria of the program outlined below will be admitted to Mines at no point before the student's senior year at CMU. The student will be admitted to Mines as a Special Status graduate student. Upon successful completion of the undergraduate degree at CMU and after meeting the Mines admission criteria, students will be admitted into the Mineral and Energy Economics MS non-thesis degree program and will be complete the MS non-thesis degree in two semesters.

CMU Students must satisfy Mines Graduate Admissions requirements as specified in the Mines catalog in effect at the time the student's application. Students who meet the admission standards are guaranteed admission into the program. Students must also meet the following requirements:

a. Students must apply for graduate admissions before the fall deadline and no earlier than before starting the final two semesters (senior year) at CMU
b. When applying, students must select the CMU Combine Undergraduate/Graduate (4+1) program on the admissions application. Official Mines approval must be granted to CMU students before the student is able to formally enter into program (4+1) agreement.
c. Official approval and recommendation from CMU department chair must be submitted at time of application.
d. Official transcripts from CMU must be submitted at the time of application to Mines and again after the undergraduate degree is conferred, but prior to the start of the term at Mines as a degree-seeking student.
e. The official final transcript must meet the minimum cumulative GPA that is required for admission to the Mines program. Completion of CMU Bachelor's Degree within 24 months of entering the 4+1 agreement is required.

## Application procedures and deadlines

It is recommended that students talk to their CMU energy management/landman advisor or department chair and the Mines Mineral and Energy Economics program director about the admissions process from CMU to Mines prior to the last two semesters of their undergraduate program. Admissions deadlines can be found at https://mines.edu/undergraduate-admissions/.

## Tuition

Residency status for tuition purposes will be determined by what is provided on the admissions application.

## Enrollment Guidelines

Students will be expected to meet CMU Bachelor of Business Administration Energy Management/Landman graduation requirements. Other enrollment guidelines include the following:

**Courses Required**

| | | |
|---|---|---|
| During the student's final two semesters at CMU, students will complete at least two of these three 400 level courses at CMU | | |
| EMGT440 | ENERGY LAND PRACTICES | 3.0 |
| EMGT450 | ENERGY LAND PRACTICES II | 3.0 |
| EMGT410 | ENERGY REGULATION AND COMPLIANCE | 3.0 |
| **Students must receive a grade of B or higher.** | | |
| Students will be eligible to transfer six (6) credits of 500-level courses from CMU (which were not used to meet any CMU graduation requirement) to Mines per Mines transfer policy. | | |
| Any 500-level courses from CMU | | |

After completion of their CMU Bachelor of Business Administration Energy Management/Landman degree, students will be fully admitted into the Mineral and Energy Economics Mines non-thesis graduate degree program.

Once being fully admitted to Mines, students will be required to fall under Mines degree requirements of the catalog in which they are first enrolled at Mines. Students that desire to complete the program in one year will be required to enroll in at least 24 credits (12 credits each semester) across the fall and spring semesters at Mines in order to complete the program in one year.

## Course Requirements at Mines

These credit hours must be from an approved list of courses. Students are advised to contact the graduate program manager [or equivalent] of the Mineral and Energy Economics program regarding the specific terms and eligible courses for which this agreement applies.

### Non-Thesis option

| | | |
|---|---|---|
| **Core Courses** | | |
| EBGN510 | NATURAL RESOURCE ECONOMICS (Fall) | 3.0 |
| EBGN509 | MATHEMATICAL ECONOMICS (Fall) | 3.0 |
| EBGN521 | MICROECONOMICS OF MINERAL AND ENERGY MARKETS (Spring) | 3.0 |
| EBGN590 | ECONOMETRICS I (Spring) | 3.0 |
| **Approved Electives** | | |
| Number depends upon 500-level credit transfers from CMU | | 12.0-18.0 |
| CMU 400-level electives – at least two of three | | 6.0-9.0 |
| **Total Semester Hrs** | | **30-39** |

## Special Provision for recent CMU Alumni

In an effort to serve students who have previously graduated from CMU, Mines will allow students who have graduated from CMU Bachelor of Business Administration Energy Management/Landman since spring 2016 to participate.

## Graduation

Students must complete all degree requirements as published in the Mines Graduate catalog.

## V. Western Colorado University Combined Undergraduate / Graduate Degree Program

Please see the Mines Registrar Transfer Agreements webpage for detailed information.

Colorado School of Mines shares a Memorandum of Understanding (MoU) with Western Colorado University. Through this program Colorado School of Mines (Mines) and Western Colorado University (Western), jointly provide opportunity to transition Western's Bachelor of Business Administration, Emphasis in Energy Management graduates to Mines in order to earn a MS non-thesis degree. This MoU grants students with the opportunity to apply up to 6 undergraduate-coursework credits applied to their Western degree toward their Mines graduate-degree requirements, while also waived graduate admissions application fee, waived requirement for three letters of recommendation, and exemption from submitting GRE test scores.

Western students who successfully pass courses and meet the admission criteria of the program outlined below will be admitted to Mines at no point before the student's senior year at Western. The student will be admitted to Mines as a special status graduate student. Upon successful completion of the undergraduate degree at Western and after meeting the Mines admission criteria, students will be admitted into the Mineral and Energy Economics MS non-thesis degree program and will be complete the MS non-thesis degree in two semesters.

Western Students must satisfy Mines Graduate Admissions requirements as specified in the Mines catalog in effect at the time the student's application. Students who meet the admission standards are guaranteed admission into the program. Students must also meet the following requirements:

a. Students must apply for graduate admissions before the fall deadline and no earlier than before starting the final two semesters (senior year) at Western.
b. When applying, students must select the Western Combine Undergraduate/Graduate (4+1) program on the admissions application. Official Mines approval must be granted to Western students before the student is able to formally enter into program (4+1) agreement.
c. Official approval and recommendation from Western department chair must be submitted at time of application.
d. Official transcripts from Western must be submitted at the time of application to Mines and again after the undergraduate degree is conferred, but prior to the start of the term at Mines as a degree-seeking student.
e. The official final transcript must meet the minimum cumulative GPA that is required for admission to the Mines program. Completion of CMU Bachelor's Degree within 24 months of entering the 4+1 agreement is required.

## Application procedures and deadlines

It is recommended that students talk to their Western Energy Management advisor or department chair and the Mines Mineral and Energy Economics program director about the admissions process from Western to Mines prior to the last two semesters of their undergraduate program. Admissions deadlines can be found online at https://mines.edu/undergraduate-admissions/.

## Tuition

Residency status for tuition purposes will be determined by what is provided on the admissions application. Refer to the Admissions webpage for residency information at https://www.mines.edu/graduate-admissions/.

## Enrollment Guidelines

Students will be expected to meet Western Bachelor of Business Administration, Emphasis in Energy Management graduation requirements. Other enrollment guidelines include the following:

| | | |
|---|---|---|
| **Course Required** | | |
| During the student's final two semesters at Western, students will complete at least two of these six 400 level courses at Western | | |
| BUAD410 | WATER LAW OR ENVIRONMENTAL LAW | 3.0 |
| BUAD415 | PORTFOLIO MANAGEMENT | 3.0 |
| BUAD420 | OIL AND GAS LAW OR ENERGY LAW | 3.0 |
| BUAD421 | ENERGY CONTRACTS | 3.0 |
| BUAD460 | ADVANCED MANAGERIAL FINANCE | 3.0 |
| BUAD495 | PROSPECT ECONOMICS AND EVALUATION | 3.0 |
| **Students must receive a grade of B or higher.** | | |
| Students will be eligible to transfer six (6) credits of 500 or 600-level courses from Western (which were not used to meet any Western graduation requirement) to Mines per Mines transfer policy. | | |
| Any 500-level courses from Western | | |

After completion of their Western Bachelor of Business Administration, Emphasis in Energy Management degree, students will be fully admitted into the Mineral and Energy Economics Mines non-thesis graduate degree program.

Once being fully admitted to Mines, students will be required to fall under Mines degree requirements of the catalog in which they are first enrolled at Mines. Students that desire to complete the program in one year will be required to enroll in at least 24 credits (12 credits each semester) across the fall and spring semesters at Mines in order to complete the program in one year.

## Course Requirements at Mines

These credit hours must be from an approved list of courses. Students are advised to contact the graduate program manager, or equivalent, of the Mineral and Energy Economics program regarding the specific terms and eligible courses for which this agreement applies.

### Non-thesis option

| | | |
|---|---|---|
| **Core Courses** | | |
| EBGN510 | NATURAL RESOURCE ECONOMICS (Fall) | 3.0 |
| EBGN509 | MATHEMATICAL ECONOMICS (Fall) | 3.0 |
| EBGN521 | MICROECONOMICS OF MINERAL AND ENERGY MARKETS (Spring) | 3.0 |
| EBGN590 | ECONOMETRICS I (Spring) | 3.0 |
| **Approved Electives** | | |
| Number depends upon 500-level credit transfers from Western | | 12.0-18.0 |
| Western 400-level electives – at least two of six | | 6.0-9.0 |
| **Total Semester Hrs** | | **30-39** |

## Graduation

Students must complete all degree requirements as published in the Mines Graduate catalog.

## VI. Dual Degree

The MS degree may be combined with a second degree from the IFP School (Paris, France) in Petroleum Economics and Management (see https://www.ifp.fr). This dual-degree program is geared to meet the needs of industry and government. Our unique program trains the next generation of technical, analytical, and managerial professionals vital to the future of the petroleum and energy industries

These two world-class institutions offer a rigorous and challenging program in an international setting. The program gives a small elite group of students a solid economics foundation combined with quantitative business skills, the historical and institutional background, and the interpersonal and intercultural abilities to succeed in the fast-paced, global world of oil and gas.

Degrees: After studying in English for only 16 months (eight months at Mines and eight months at IFP) the successful student of Petroleum Economics and Management (PEM) receives not one but two degrees:

- Master of Science in Mineral and Energy Economics from Mines and
- Diplôme D'Ingénieur or Mastère Spécialisé from IFP

Important: Applications for admission to the joint degree program should be submitted for consideration by March 1st to begin the program the following fall semester in August. A limited number of students are selected for the program each year.

## Prerequisites for the Mineral and Energy Economics Programs

Students must have completed the following undergraduate prerequisite courses prior to beginning the program with a grade of B or better:

1. Principles of Microeconomics
2. One semester of college-level Calculus
3. Probability and Statistics

## Engineering and Technology Management (ETM) Master of Science Program Requirements

Students choose either the thesis or non-thesis option and complete a minimum of 30 credits. Initial admission is only to the non-thesis program. Admission to the thesis option requires subsequent application after admission to the ETM program.

| | |
|---|---|
| **Non-thesis option** | |
| Core courses | 15.0 |
| Elective courses | 15.0 |
| **Total Semester Hrs** | **30.0** |

| | |
|---|---|
| **Thesis option** | |
| Core courses | 15.0 |
| Research credits | 6.0 |
| Elective courses | 9.0 |
| **Total Semester Hrs** | **30.0** |

Students must receive approval from their advisor in order to apply non-EB division courses toward their ETM degree. Thesis students are required to complete 6 credits of thesis credit and complete a master's level thesis under the direct supervision of the student's thesis advisor.

## Further Degree Requirements

All thesis and non-thesis ETM MS students have four additional degree requirements:

1. the Executive-in-Residence seminar series
2. the ETM Communications workshop
3. the Leadership and Team Building workshop
4. Introductory Python Programming workshop

All students are required to attend the ETM Program Executive-in-Residence seminar series during their first spring semester of study in the ETM Program. The Executive-in-Residence series features executives from industry who pass on insight and knowledge to graduate students preparing for positions in industry. This series facilitates active involvement in the ETM program by industry executives through teaching, student advising activities and more. Every spring semester the Executive-in-Residence will present a number of seminars on a variety of topics related to leadership and strategy in the engineering and technology sectors.

In addition, all students in their first fall semester of study in the ETM Program are required to attend a Communications workshop, a Leadership and Team Building workshop and an Introductory Python Programming workshop. The Communications workshop will provide students with a comprehensive approach to good quality communication skills, including presentation proficiency, organizational skills, professional writing skills, meeting management, as well as other professional communication abilities. This workshop is designed to better prepare students for the ETM learning experience and their professional careers. The Leadership and Team Building workshop consists of non-competitive games, trust exercises and problem-solving challenges and will introduce students to one another and provide opportunities to learn and practice leadership and team skills. Finally, the Python Programming workshop provides an introduction to using Python to solve analytical problems.

## Mines' Combined Undergraduate/Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits toward the ETM degree under the following circumstances:

(i) Any 6 credits of ETM graduate courses can be double counted.
(ii) Any graduate course that has been approved by the ETM program committee as an ETM elective in a student's program of study.

These courses must have been passed with a B or better, not be substitutes for required coursework, and meet all other University,

**Transfer Credits**

Students who enter the MS in Engineering and Technology Management program may transfer up to 6 graduate course credits into the degree program. The student must have achieved a grade of B or better in all graduate transfer courses and the transfer credit must be approved by the student's advisor and the director of the ETM program.

## Required Curriculum MS Degree Engineering and Technology Management

Thesis and non-thesis students are required to complete the following 15 hours of core courses which ideally should be taken at the first available opportunity:

**a. Core Courses**

| | | |
|---|---|---|
| EBGN525 | BUSINESS ANALYTICS | 3.0 |
| EBGN540 | ACCOUNTING AND FINANCE | 3.0 |
| EBGN553 | PROJECT MANAGEMENT | 3.0 |
| EBGN563 | MANAGEMENT OF TECHNOLOGY AND INNOVATION | 3.0 |
| EBGN585 | ENGINEERING AND TECHNOLOGY MANAGEMENT CAPSTONE (to be taken during the final semester of coursework) | 3.0 |
| **Total Semester Hrs** | | **15.0** |

**b. Elective courses (15 credits required for non-thesis option or 9 credits required for thesis option)**

| | | |
|---|---|---|
| **Engineering Management and Analytic Methods** | | |
| EBGN526 | STOCHASTIC MODELS IN MANAGEMENT SCIENCE | 3.0 |
| EBGN527 | BUSINESS OPTIMIZATION MODELS | 3.0 |
| EBGN528 | INDUSTRIAL SYSTEMS SIMULATION | 3.0 |
| EBGN529 | HEALTH SYSTEMS ENGINEERING ANALYTICS | 3.0 |
| EBGN555 | LINEAR PROGRAMMING | 3.0 |
| EBGN559 | SUPPLY CHAIN ANALYTICS | 3.0 |
| EBGN560 | DECISION ANALYTICS | 3.0 |
| EBGN571 | MARKETING ANALYTICS | 3.0 |
| **Technology Management and Innovation** | | |
| EBGN562 | STRATEGIC DECISION MAKING | 3.0 |
| EBGN565 | MARKETING FOR TECHNOLOGY-BASED COMPANIES | 3.0 |
| EBGN566 | TECHNOLOGY ENTREPRENEURSHIP | 3.0 |
| EBGN572 | INTERNATIONAL BUSINESS STRATEGY | 3.0 |
| EBGN576 | MANAGING AND MARKETING NEW PRODUCT DEVELOPMENTS | 3.0 |
| EBGN577 | LEADING & MANAGING HIGH PERFORMING TEAMS | 3.0 |
| EBGN578 | BUSINESS OPERATIONS AND SUPPLY CHAIN MANAGEMENT | 3.0 |

Graduate Certificate in Resource Commodity Analytics

The graduate certificate requirements are to complete at least one course from the list of required courses, and 9 additional credits either from the required courses list or the electives list. EBGN599 independent study may satisfy no more than 3 credits of the certificate requirement. EBGN540 requires consent of instructor. Full-time students intending to complete the certificate in one semester must enter in the fall; part-time students can enter in the spring or fall.

Required courses (complete one of the following):

| | | |
|---|---|---|
| EBGN510 | NATURAL RESOURCE ECONOMICS | 3.0 |
| EBGN590 | ECONOMETRICS I | 3.0 |

Elective courses:

| | | |
|---|---|---|
| EBGN504 | ECONOMIC EVALUATION AND INVESTMENT DECISION METHODS | 3.0 |
| EBGN540 | ACCOUNTING AND FINANCE | 3.0 |
| EBGN560 | DECISION ANALYTICS | 3.0 |
| EBGN575 | ADVANCED MINING AND ENERGY ASSET VALUATION | 3.0 |
| EBGN594 | TIME-SERIES ECONOMETRICS | 3.0 |
| EBGN632 | PRIMARY FUELS | 3.0 |
| EBGN645 | COMPUTATIONAL ECONOMICS | 3.0 |
| EBGN599 | INDEPENDENT STUDY | 3.0 |

## Graduate Certificate in Business Analytics

```
The certificate is an online or residential program. The
 requirements are to complete the core course and two elective
 courses:
```

**Core Course**

| | | |
|---|---|---|
| EBGN525 | BUSINESS ANALYTICS | 3.0 |

**Elective Courses**

| | | |
|---|---|---|
| EBGN559 | SUPPLY CHAIN ANALYTICS | 3.0 |
| EBGN560 | DECISION ANALYTICS | 3.0 |
| EBGN571 | MARKETING ANALYTICS | 3.0 |

Course substitutions may be approved on a case-by-case basis by the certificate director. Completing the certificate will also position students to apply to either the master of science in engineering and technology management degree or the master of science in data science degree, as the certificate courses can be applied to either degree.

## Graduate Certificate in Product Management

The certificate is an online or residential program. The requirements are to complete the core course and two elective courses:

**Core Course**

| | | |
|---|---|---|
| EBGN563 | MANAGEMENT OF TECHNOLOGY AND INNOVATION | 3.0 |

**Elective Courses**

| | | |
|---|---|---|
| EBGN553 | PROJECT MANAGEMENT | 3.0 |
| EBGN565 | MARKETING FOR TECHNOLOGY-BASED COMPANIES | 3.0 |
| EBGN577 | LEADING & MANAGING HIGH PERFORMING TEAMS | 3.0 |

Course substitutions may be approved on a case-by-case basis by the certificate director. Completing the certificate will also position students to complete the master of science in engineering and technology management degree as all the certificate courses can be applied to this degree.

## Courses

**EBGN502. POLITICAL ECONOMY OF THE ENERGY TRANSITION. 3.0 Semester Hrs.**
This course provides an overview of economics, business, and political topics that are commonly found in the energy transition. Many of the assignments relate back to skills that are needed to interact with economics, business, and policy professionals. The course is designed for students with little, if any, social science or business training. Students will build a basic knowledge of economics, finance, and business issues that are relevant to energy markets and industries.
**Course Learning Outcomes**

- 1. Interpret and assess basic economic intuition and lingo so that one can contribute to projects on the business side
- 2. Evaluate and critique standard investment analysis techniques
- 3. Describe common market structures for natural resource commodities and theorize its impact on firm behavior
- 4. Name the location of basic data on energy price, production, and consumption and demonstrate its evolution over time
- 5. Analyze the politics behind an aspect of the energy transition
- 6. Identify key political actors in the transition
- 7. Design a presentation for the business community that provides a clear value proposition.
- 8. Execute an "elevator pitch" (concise and persuasive speech to spark interest) about an energy/natural resource topic.

**EBGN504. ECONOMIC EVALUATION AND INVESTMENT DECISION METHODS. 3.0 Semester Hrs.**
Time value of money concepts of present worth, future worth, annual worth, rate of return and break-even analysis are applied to after-tax economic analysis of mineral, petroleum and general investments. Related topics emphasize proper handling of (1) inflation and escalation, (2) leverage (borrowed money), (3) risk adjustment of analysis using expected value concepts, and (4) mutually exclusive alternative analysis and service producing alternatives. Case study analysis of a mineral or petroleum investment situation is required. Students may not take EBGN504 for credit if they have completed EBGN321.

**EBGN509. MATHEMATICAL ECONOMICS. 3.0 Semester Hrs.**
This course reviews and re-enforces the mathematical and computer tools that are necessary to earn a graduate degree in Mineral Economics. It includes topics from differential and integral calculus; probability and statistics; algebra and matrix algebra; difference equations; and linear, mathematical and dynamic programming. It shows how these tools are applied in an economic and business context with applications taken from the mineral and energy industries. It requires both analytical as well as computer solutions. At the end of the course you will be able to appreciate and apply mathematics for better personal, economic and business decision making. Prerequisites: Principles of Microeconomics, and MATH111.

**EBGN510. NATURAL RESOURCE ECONOMICS. 3.0 Semester Hrs.**
The threat and theory of resource exhaustion; commodity analysis and the problem of mineral market instability; cartels and the nature of mineral pricing; the environment; government involvement; mineral policy issues; and international mineral trade. This course is designed for entering students in mineral economics. Prerequisite: Principles of Microeconomics.

**EBGN511. MICROECONOMICS. 3.0 Semester Hrs.**
(I, II, S) This is a graduate course dealing with applied microeconomic theory. The course concentrates on the behavior of individual segments of the economy, the theory of consumer behavior and demand, duality, welfare measures, policy instruments, preferences over time and states of nature, and the fundamentals of game theory. Prerequisites: MATH111, EBGN509. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- No change

**EBGN512. MACROECONOMICS. 3.0 Semester Hrs.**
This course will provide an introduction to contemporary macroeconomic concepts and analysis. Macroeconomics is the study of the behavior of the economy as an aggregate. Topics include the equilibrium level of inflation, interest rates, unemployment and the growth in national income. The impact of government fiscal and monetary policy on these variables and the business cycle, with particular attention to the effects on the mineral industry. Prerequisites: Principles of Microeconomics, MATH111.

**EBGN515. ECONOMICS AND DECISION MAKING. 3.0 Semester Hrs.**
The application of microeconomic theory to business strategy. Understanding the horizontal, vertical, and product boundaries of the modern firm. A framework for analyzing the nature and extent of competition in a firm's dynamic business environment. Developing strategies for creating and sustaining competitive advantage.

**EBGN521. MICROECONOMICS OF MINERAL AND ENERGY MARKETS. 3.0 Semester Hrs.**
(I) This is a graduate course dealing with applied microeconomic theory. This course concentrates on the behavior of the minerals and energy segment of the economy, the theory of production and cost, the theory of consumer behavior and demand, derived demand, price and output level determination by firms, and the competitive structure of product and input markets. Prerequisites: MATH111, EBGN509. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- No change

**EBGN523. MINERAL AND ENERGY POLICY. 3.0 Semester Hrs.**
(II) An analysis of current topics in the news in mineral and energy issues through the lens of economics. Since many of the topics involve government policy, the course provides instruction related to the economic foundations of mineral and energy policy analysis. 3 credit hours.

**EBGN525. BUSINESS ANALYTICS. 3.0 Semester Hrs.**
The process of converting data into meaningful insights has become critical for organizations to stay competitive. Driven by the availability of massive volumes of business data, business analytics has become instrumental in informing managerial practices and strategies in companies at every stage of their operations. This course introduces fundamental concepts for descriptive analytics and statistical methods which provide primary skills to students that enable them to use quantitative tools for organizing, processing, and critically interpreting business data. Students will learn to use data analytics toolkits and libraries in Excel and Python to address real-world business problems in a variety of industries and disciplines, including energy, production, logistics, scheduling, marketing, and finance.
**Course Learning Outcomes**

- Understand the basics of probability theory
- Gain skills in cleaning raw business data by imputing missing cells, identifying and handling outliers, eliminating unnecessary attributes using Excel
- Explore, visualize and critically interpret business data using Python
- Understand and perform linear regression analysis and interpret the results using tools in Python
- Address real-world business problems in a variety of disciplines using analytical thinking skills in cleaning, processing and analyzing raw business data and converting them into meaningful managerial insights

**EBGN526. STOCHASTIC MODELS IN MANAGEMENT SCIENCE. 3.0 Semester Hrs.**
(II) This course introduces the tools of stochastic modeling that are very useful in solving analytical problems in business. We cover methodologies that help to quantify the dynamic relationships of sequences of random events that evolve over time. Topics include static and dynamic Monte-Carlo simulation, discrete and continuous time Markov chains, probabilistic dynamic programming, Markov decision processes, queuing processes and networks, Brownian motion and stochastic control. Applications from a wide range of fields will be introduced including marketing, finance, production, logistics and distribution, energy and service systems. In addition to an intuitive understanding of analytical techniques to model stochastic processes, the course emphasizes how to use related software packages for managerial decision-making. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Explain the basics of probability theory.
- Use conditional probability and expectations in real-world problems.
- Explain and model systems by applying Markov Chains to stochastic processes in discrete and continuous time.
- Explain and apply Poisson processes to solve problems involving random events occurring over time.
- Utilize transition probability matrices to determine the long-term behavior of Markov chains.
- Apply basic principles of queueing theory and models to analyze the performance of complex service systems.
- Implement simulation techniques to explore the behavior stochastic systems and interpret the results.

**EBGN527. BUSINESS OPTIMIZATION MODELS. 3.0 Semester Hrs.**
Business optimization is one of the most important actions taken by businesses at the strategic, tactical, operational levels in order to stay competitive and successful. Prescriptive analytics aim to identify the optimal solutions for organizations. This course provides quantitative skills to solve real-world business problems using analytics by focusing on the art of model building using linear, integer and mixed-integer programming for business applications in several areas such as production, supply chain management, and finance. To this end, several real-world business problems will be examined. It also provides insights into specially structured models, and fundamental skills on model enhancement techniques. Prerequisite: Admission to the ETM program or permission of the instructor.
**Course Learning Outcomes**

- Develop a high-level understanding of what prescriptive analytics is and its difference from descriptive and predictive analytics.
- Develop skills on the art of formulating deterministic optimization models for business problems.
- Develop insights into specially structured models that provide skills in identifying and using them in business applications.
- Identify objectives, limitations and necessary inputs for business problems.
- Develop optimization models for business problems and solve them to obtain optimal decisions using AMPL with different solvers (e.g., CPLEX, GUROBI).

- Gain skills in model enhancement techniques to develop efficient optimization models.
- Develop skills in analyzing the optimal solution and extracting insights from it.

**EBGN528. INDUSTRIAL SYSTEMS SIMULATION. 3.0 Semester Hrs.**
The course focuses on creating computerized models of real or proposed complex systems for performance evaluation. Simulation provides a cost effective way of pre-testing proposed systems and answering "what-if" questions before incurring the expense of actual implementations. The course is instructed in the state-of-the-art computer lab (CTLM), where each student is equipped with a personal computer and interacts with the instructor during the lecture. Professional version of a widely used commercial software package, "Arena", is used to build models, analyze and interpret the results. Other business analysis and productivity tools that enhance the analysis capabilities of the simulation software are introduced to show how to search for optimal solutions within the simulation models. Both discrete-event and continuous simulation models are covered through extensive use of applications including call centers, various manufacturing operations, production/inventory systems, bulk-material handling and mining, port operations, high-way traffic systems and computer networks.
**Course Learning Outcomes**

- Identify appropriate systems for simulation modeling.
- Use probability models to determine the probability or expectation of events.
- Build single-queue single-server queuing models and provide steady-state, long-run performance values.
- Model and build basic simulations using an Excel spreadsheet.
- Model and build more complex simulations using Arena.
- Select reasonable probability distributions for predicting future events.
- Analyze simulation output to drive system evaluation and decisions.
- Model a real or proposed system as a simulation project and make recommendations based on the results.

**EBGN529. HEALTH SYSTEMS ENGINEERING ANALYTICS. 3.0 Semester Hrs.**
This course provides skills on modeling and forecasting through the avenue of a hospital-wide learning system to develop, implement, and assess clinical operational excellence strategies for care delivery transformation across diverse health system settings. This course utilizes the science of improvement to understand and prioritize solutions to reduce flow failures and delays and achieve efficient hospital-wide patient flow, which is crucial for safe and quality care and effective utilization of healthcare resources. The emphasis is on the DMAIC problem-solving approach that drives Lean Six Sigma performance improvement project within the macro system dynamics. Prerequisite: None Co-requisite: None.
**Course Learning Outcomes**

- Learning Outcome 1 (LO1): 'D' Define
- Learning Outcome 2 (LO2): 'M' Measure
- Learning Outcome 3 (LO3): 'A' Analyze
- Learning Outcome 4 (LO4): 'I' Improve
- Learning Outcome 5 (LO5): 'C' Control

**EBGN530. ECONOMICS OF INTERNATIONAL ENERGY MARKETS. 3.0 Semester Hrs.**
Application of models to understand markets for oil, gas, coal, electricity, and renewable energy resources. Models, modeling techniques, and issues included are supply and demand, market structure, transportation models, game theory, futures markets, environmental issues, energy policy, energy regulation, input/output models, energy conservation, and dynamic optimization. The emphasis in the course is on the development of appropriate models and their application to current issues in energy markets. Prerequisites: Principles of Microeconomics, MATH111, EBGN509, EBGN510, EBGN511.

**EBGN535. ECONOMICS OF METAL INDUSTRIES AND MARKETS. 3.0 Semester Hrs.**
(I, II, S) Metal supply from main product, byproduct, and secondary production. Metal demand and intensity of use analysis. Market organization and price formation. Public policy, comparative advantage, and international metal trade. Metals and economic development in the developing countries and former centrally planned economies. Environmental policy and mining and mineral processing. Students prepare and present a major research paper. Prerequisites: EBGN201, MATH111, EBGN509, and EBGN510. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Same as before

**EBGN536. MINERAL POLICIES AND INTERNATIONAL INVESTMENT. 3.0 Semester Hrs.**
Identification and evaluation of international mineral investment policies and company responses using economic, business and legal concepts. Assessment of policy issues in light of stakeholder interests and needs. Theoretical issues are introduced and then applied to case studies, policy drafting, and negotiation exercises to assure both conceptual and practical understanding of the issues. Special attention is given to the formation of national policies and corporate decision making concerning fiscal regimes, project financing, environmental protection, land use and local community concerns and the content of exploration and extraction agreements. Prerequisites: Principles of Microeconomics, MATH111, EBGN509, EBGN510, EBGN511.

**EBGN537. ECONOMICS OF WATER. 3.0 Semester Hrs.**
(II) This course seeks to develop the underlying economic logic of water use and how policy impacts the allocation of water in our economy. Water is a critical input for a number of sectors; from our basic sustenance to agriculture production, from industrial processes to ecological services, and from mineral extraction to energy production. Meanwhile, the supply of water is highly variable across space and through time while pollutants can further diminish the useable extent, making the policies to allocate and manage the resource central to understanding how the resource is utilized. The course will survey topics across sectors and water sources while applying economic theory and empirical/policy analysis. Prerequisite: EBGN509 or MATH213 or GEGN580. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- 1. Economic modelling of water systems
- 2. Empirical assessment of water policies
- 3. Valuation techniques for water resources
- 4. How institutional structure effect development
- 5. Economic tools to assess water allocation and water pollution
- 6. Application to specific sectors

**EBGN540. ACCOUNTING AND FINANCE. 3.0 Semester Hrs.**
(I) Included are the relevant theories associated with capital budgeting, financing decisions, and dividend policy. This course provides an in-depth study of the theory and practice of corporate accounting and financial management including a study of the firm's objectives, investment decisions, long-term financing decisions, and working capital management. Preparation and interpretation of financial statements and the use of this financial information in evaluation and control of the organization. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Evaluate financial performance, financial position, and prospects in terms of financial risk, liquidity, solvency, efficiency, company profitability, growth outlook and comparisons to other companies.
- Interpret financial statements and determine how they reflect operating results.
- Allocate capital optimally by selecting the most attractive investments using time value of money principles, discounted cash flow and appropriate risk-return measures.
- Evaluate financial results from the viewpoint of various stakeholders (investors, suppliers, lenders, etc.) by looking at what's most important from their various perspectives.
- Predict the impact of management decisions on key financial measures that include profitability, efficiency, capital needs, cost structure, etc.
- Calculate the true economic value added for a given company, based on financial results.
- Estimate cost of debt, cost of equity and weighted average costs of capital (WACC) and evaluate default risk to determine the best way for a company to raise financing.
- Build financial models to value assets, evaluate capital investment alternatives and forecast capital needs.

**EBGN541. INTERNATIONAL TRADE. 3.0 Semester Hrs.**
Theories and evidence on international trade and development. Determinants of static and dynamic comparative advantage. The arguments for and against free trade. Economic development in nonindustrialized countries. Sectoral development policies and industrialization. The special problems and opportunities created by extensive mineral resource endowments. The impact of value-added processing and export diversification on development. Prerequisites: Principles of Microeconomics, MATH111, EBGN509, EBGN511.

**EBGN542. ECONOMIC DEVELOPMENT. 3.0 Semester Hrs.**
Role of energy and minerals in the development process. Sectoral policies and their links with macroeconomic policies. Special attention to issues of revenue stabilization, resource largesse effects, downstream processing, and diversification. Prerequisites: Principles of Microeconomics, MATH111, EBGN509, EBGN511, EBGN512.

**EBGN546. INVESTMENT AND PORTFOLIO MANAGEMENT. 3.0 Semester Hrs.**
This course covers institutional information, valuation theory and empirical analysis of alternative financial investments, including stocks, bonds, mutual funds, ETS, and (to a limited extent) derivative securities. Special attention is paid to the role of commodities (esp. metals and energy products) as an alternative investment class. After an overview of time value of money and arbitrage and their application to the valuation of stocks and bonds, there is extensive treatment of optimal portfolio selection for risk averse investors, mean-variance efficient portfolio theory, index models, and equilibrium theories of asset pricing including the capital asset pricing model (CAPM) and arbitrage pricing theory (APT). Market efficiency is discussed, as are its implications for passive and active approaches to investment management. Investment management functions and policies, and portfolio performance evaluation are also considered. Prerequisites: Principles of Microeconomics, MATH111, MATH530.

**EBGN547. FINANCIAL RISK MANAGEMENT. 3.0 Semester Hrs.**
Analysis of the sources, causes and effects of risks associated with holding, operating and managing assets by individuals and organizations; evaluation of the need and importance of managing these risks; and discussion of the methods employed and the instruments utilized to achieve risk shifting objectives. The course concentrates on the use of derivative assets in the risk management process. These derivatives include futures, options, swaps, swaptions, caps, collars and floors. Exposure to market and credit risks will be explored and ways of handling them will be reviewed and critiqued through analysis of case studies from the mineral and energy industries. Prerequisites: Principles of Microeconomics, MATH111, MATH530, EBGN505; EBGN545 or EBGN546. Recommended: EBGN509, EBGN511.

**EBGN553. PROJECT MANAGEMENT. 3.0 Semester Hrs.**
(I, II) Project management has evolved into a business process broadly used in organizations to accomplish goals and objectives through teams. This course covers the essential principles of traditional project management consistent with professional certification requirements (the Project Management Institute's PMP certification) as well as an introduction to current agile project management methodologies. The traditional project management phases of project initiation, planning, execution, monitoring and control, and project closure are covered including related scheduling, estimating, risk assessment and other analytical tools. Students will gain experience using Microsoft Project. Organizational structure and culture issues are analyzed to understand how they can impact project management success, and the concepts of project portfolios and project programs are applied from the organizational perspective. Agile project management methodologies are introduced, including adaptive and iterative processes, scrum, lean and other agile tools and techniques. By the end of the course, students will understand how traditional and agile project. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Create a work breakdown structure and estimate for a proposed project using an Excel spreadsheet.
- Manage the multiple constraints of a technology development project using a project management project or challenging scenarios in a project management simulation game.
- Judge the opportunities and challenges of high-performance teams, including leadership skills and personnel management through case studies and in class discussions.
- Investigate the roles and responsibilities of a Project Manager and stakeholders using a RACI chart in an in-class exercise.
- Define the tools and techniques for small, medium and large projects in exercises and a Mid-Term exam.
- Identify project management techniques that were successful or failures using case studies and class discussions.
- Define a basic project risk assessment with impact and probability using exercises.
- Assess Agile project management and how it differs from traditional project management through class lectures.
- Manage a project from start to finish including problem-solving and management recommendations based on quantitative analysis.

- Apply presentation, leadership and group management skills to provide a professional proposal and presentation of an approved team project.

**EBGN555. LINEAR PROGRAMMING. 3.0 Semester Hrs.**
This course addresses the formulation of linear programming models, examines linear programs in two dimensions, covers standard form and other basics essential to understanding the Simplex method, the Simplex method itself, duality theory, complementary slackness conditions, and sensitivity analysis. As time permits, multi-objective programming and stochastic programming are introduced. Applications of linear programming models discussed in this course include, but are not limited to, the areas of manufacturing, finance, energy, mining, transportation and logistics, and the military. 3 hours lecture; 3 semester hours.

**EBGN559. SUPPLY CHAIN ANALYTICS. 3.0 Semester Hrs.**
The focus of the course is to show how a firm can achieve better "supply-demand matching" through the implementation of rigorous mathematical models and various operational/tactical strategies. We look at organizations as entities that must match the supply of what they produce with the demand for their products. A considerable portion of the course is devoted to mathematical models that treat uncertainty in the supply-chain. Topics include managing economies of scale for functional products, managing market-mediation costs for innovative products, make-to order versus make-to-stock systems, quick response strategies, risk pooling strategies, supply-chain contracts and revenue management. Additional "special topics" may be introduced, such as reverse logistics issues in the supply-chain or contemporary operational and financial hedging strategies, as time permits.
**Course Learning Outcomes**

- Apply probability concepts to analyze uncertainties in supply chain scenarios.
- Implement demand forecasting techniques to predict future inventory needs in various supply chain contexts.
- Utilize inventory theory and models, such as EOQ and newsvendor, to determine optimal inventory levels.
- Formulate the facility location problems, traveling salesman problem, and vehicle routing problem to analyze and improve the supply chain networks and determine efficient routes and logistics performance.
- Identify assumptions of each model and their implications.
- Construct a model based on explicit assumptions and explain the findings/results.

**EBGN560. DECISION ANALYTICS. 3.0 Semester Hrs.**
Introduction to the science of decision making and risk theory. Application of decision analysis and utility theory to the analysis of strategic decision problems. Focuses on the application of quantitative methods to business problems characterized by risk and uncertainty. Choice problems such as decisions concerning major capital investments, corporate acquisitions, new product introductions, and choices among alternative technologies are conceptualized and structured using the concepts introduced in this course.
**Course Learning Outcomes**

- Build an economic cashflow model in Excel and derive insights from the results.
- Create an Influence Diagram to represent the relationships between uncertainties and decisions in a given business situation.
- Design a decision tree model using Precision Tree software, modeling the situation faced by a company in a case study and generating a recommended course of action based on mean Net Present Value.
- Design a Monte Carlo simulation model using @Risk software, modeling the situation faced by a company in a case study and calculating common financial metrics (NPV, IRR, capital efficiency), and generate a recommended course of action based on the results from that model.
- Formulate a Value-of-Information (VOI) analysis to recommend a decision regarding whether a company should pay a specific amount for a given piece of information.
- Derive valid P10, P50, and P90 inputs (10th, 50th, and 90th percentiles, respectively) for a probabilistic model by conducting Subject-Matter-Expert (SME) interviews for specific uncertainties in a way that mitigates known human biases (both cognitive and motivational). Valid model outputs cannot be generated without valid inputs.
- Develop an approach to applying one's risk tolerance at the portfolio level.
- Compare and contrast applying one's risk tolerance at the portfolio level with applying one's risk tolerance at the individual project level, in terms understandable to someone with little to no background in business or statistics.

**EBGN562. STRATEGIC DECISION MAKING. 3.0 Semester Hrs.**
(I, II, S) This course covers how to unwind complex situations to gain clarity and enable confident decisions. The focus is on thinking as opposed to calculating, framing the problem correctly, ensuring clarity around the objectives, developing creative alternative strategies, and qualitatively evaluating these alternatives. Tools for accomplishing these goals will be introduced. Discussion topics include common psychological biases and traps, scenario analysis, game theory, cultural influences, and decision making in complex (as opposed to merely complicated) systems. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Design a good decision-making process for complex problems.
- Derive different types of key issues from difficult situations and manage them effectively.
- Develop methods and tools to characterize uncertainty appropriately in decision making.
- Create objective hierarchies.
- Generate creative alternative strategies.
- Modify the decision process to avoid and mitigate the pitfalls that comes from human psychological weaknesses.
- Develop effective solutions to both complicated and complex problems.

**EBGN563. MANAGEMENT OF TECHNOLOGY AND INNOVATION. 3.0 Semester Hrs.**
Lectures, case studies and reading assignments explore strategies for profiting from technology assets and technological innovation. The roles of strategy, core competencies, product and process development, manufacturing, R&D, marketing, strategic partnerships, alliances, intellectual property, organizational architectures, leadership and politics are explored in the context of technological innovation. The critical role of organizational knowledge and learning in a firm's ability to leverage technological innovation to gain competitive advantage is explored. The relationships between an innovation, the competencies of the innovating firm, the ease of duplication of the innovation by outsiders, the nature of complementary assets needed to successfully commercialize

an innovation and the appropriate strategy for commercializing the innovation are developed. Students explore the role of network effects in commercialization strategies, particularly with respect to standards wars aimed at establishing new dominant designs.

**Course Learning Outcomes**

- Analyze key theories and models of technological innovation and their relevance to various industry contexts using readings and quizzes.
- Evaluate the impact of innovation on competitive advantage and business success in technology-intensive sectors through case study discussions.
- Develop successful and unsuccessful approaches to technology commercialization using strategic management tools in case study discussions.
- Design effective strategies to foster and manage innovation in both startups and established firms.
- Distinguish the role of intellectual property in shaping technological innovation through guest speaker presentations.
- Define the challenges, obstacles and paths to success for technology company managers based on a research report based on interviews of innovation managers.
- Create a management recommendations final paper based on analysis of an innovative company through effective team collaboration, demonstrating leadership and problem-solving skills.

**EBGN565. MARKETING FOR TECHNOLOGY-BASED COMPANIES. 3.0 Semester Hrs.**

This class explores concepts and practices related to marketing in this unique, fast-paced environment, including the defining characteristics of high-technology industries; different types and patterns of innovations and their marketing implications; the need for (and difficulties in) adopting a customer-orientation; tools used to gather marketing research/ intelligence in technology-driven industries; use of strategic alliances and partnerships in marketing technology; adaptations to the "4 P's"; regulatory and ethical considerations in technological arenas.

**Course Learning Outcomes**

- Differentiate characteristics of high-technology industries versus stable industries as presented in course readings through class discussions and exams/quizzes.
- Examine patterns of innovation, and their marketing implications, within high-technology environments through class discussions, case analyses, and exams.
- Develop a customer-orientation from a high-technology environment through class discussions, case analyses, and the project.
- Assemble marketing data that guides research intelligence in technology-driven industries through class discussions, case analyses, and the project.
- Formulate the appropriate marketing mix required in a high-tech environment through case analyses and the project write-up and presentation.
- Examine the dynamics of specific high-tech companies that are based on real-life case studies through class discussions and the project.
- Select best practices for marketing efforts within high-tech companies that are based on real-life scenarios through class discussions, journal entries, and the project.
- Assemble a rigorous marketing plan with teammates based on market analysis for a high-tech industry and feedback from class discussions that can be presented as a written report and a presentation.

**EBGN566. TECHNOLOGY ENTREPRENEURSHIP. 3.0 Semester Hrs.**

Technology entrepreneurship is a distinct activity in technology enterprises and start-ups that require a disciplined approach to forming product concepts and justifying financial investment. This course covers technology categories, venture opportunity and strategy, product design, industry and competitive analysis, concept development, venture development, intellectual property, funding and financial projections. In addition, the course explores creativity, problem solving, business modeling, market analysis and business planning for technology-oriented solutions. A Venture Plan project will allow students to develop a start-up business concept with a technology product of their choosing. Venture Planning topics include: product design, product forecasting, revenue forecasting, operations planning, staffing plan, financial analysis, financial statements, funding sources and uses. A start-up venture plan will be created with 3-year projections for income statements, cashflow and balance sheet.

**Course Learning Outcomes**

- Develop a technology innovator and leader self-assessment based on strengths, goals and themes for innovation.
- Evaluate the impact of critical driving forces on the success of new ventures through analysis of case studies and technology startups using in-class discussions.
- Summarize the strategies used by investors to find and assess durable opportunities in technology entrepreneurship using the five investment factors.
- Conduct industry, market and competitive analysis of an existing start-up company in a written 5-8 page research paper.
- Create a potential small-scale solution to a plastic waste problem using the problem-solving process in a written 4-6 page paper.
- Develop a prototype of a technology product that demonstrates the application of Design Thinking to achieve a balance between aesthetic appeal and practical functionality.
- Create a comprehensive start-up Venture Plan that includes detailed financial projections and proforma financial tables.

**EBGN567. BUSINESS LAW AND ETHICS. 3.0 Semester Hrs.**

(I) This course incorporates a broad range of legal topics and ethical issues relevant to technology-based organizations, from start-ups to mature Fortune 100 international corporations. The topics encompass numerous aspects of U.S. business law, including but not limited to: the U.S. court system, contracts, e-commerce, managerial ethics, white collar crimes, early stage business formation, intellectual property, product liability, agency law, employment law, mergers and acquisitions, antitrust, and unfair competition law. The course is discussion based, with some lecture, and is 3 semester credit hours. There are no prerequisites required for this course. A significant portion of class time will be applied to exploring and discussing assigned topics through relevant abbreviated court case descriptions, ethics reader assignments and current and recent events in global business. He overall goal of this course is not to make students legal experts but to make them better managers and leaders by equipping them with relevant legal. 3 hours lecture; 3 semester hours.

**Course Learning Outcomes**

- At the conclusion of this course students will be able to: 1. Describe the sources of U.S. law and explain the differences between law, ethics and the social responsibility of business. 2. Integrate

business law considerations into business decision processes, and demonstrate how this integration can identify important questions that must be considered from a risk context. 3. Gain business skills by exercising advocacy of alternative positions in class and online discussions. 4. Analyze business cases to identify legal and ethical considerations. 5. Demonstrate how ethical issues and considerations can impact personal and managerial decisions in business organizations. 6. Define the structure of the U.S. court system, the general stages of the civil litigation process and forms of alternative dispute resolution available to commercial enterprises. 7. Apply the elements of contract formation, performance and discharge to commercial transaction scenarios to identify potential contractual legal risks and liabilities. 8. Analyze contract breach scenarios and determine damages calculations and possible equitable remedies. 9. Identify business and white-collar crimes, and describe the U.S. criminal legal procedure. 10. Define intentional and unintentional torts that can apply to business conduct, and identify activities that could expose an organization to risks of legal liability under the legal theories of negligence. 11. Describe the different forms of intellectual property protection, including patents, trademarks, copyrights and trade secrets and how they may apply to different forms of technology development. 12. Identify express and implied warranties, and define the sources of product liability. 13. Define the different types of bankruptcy available under federal law, and describe federal bankruptcy procedure. 14. Apply agency law to different employment and agency business situations to identify potential legal risks and obligations. 15. Analyze an entrepreneurial business opportunity and identify the available forms of legal entity creation applicable to those opportunities. 16. Explain the elements of good corporate governance. 17. Define three different forms of business mergers and acquisitions, and how the general antitrust laws can impact potential business combinations. 18. Identify at least three labor and employment practices that can expose businesses to legal liability.

**EBGN568. ADVANCED PROJECT ANALYSIS. 3.0 Semester Hrs.**
An advanced course in economic analysis that will look at more complex issues associated with valuing investments and projects. Discussion will focus on development and application of concepts in after-tax environments and look at other criteria and their impact in the decision-making and valuation process. Applications to engineering and technology aspects will be discussed. Effective presentation of results will be an important component of the course. Prerequisite: EBGN504.

**EBGN570. ENVIRONMENTAL ECONOMICS. 3.0 Semester Hrs.**
The role of markets and other economic considerations in controlling pollution; the effect of environmental policy on resource allocation incentives; the use of benefit/cost analysis in environmental policy decisions and the associated problems with measuring benefits and costs. Prerequisites: Principles of Microeconomics, MATH111, EBGN509, EBGN510.

**EBGN571. MARKETING ANALYTICS. 3.0 Semester Hrs.**
The purpose of this course is to gain an understanding of how data about customers and markets can be used to support and improve decision making. Using market data to evaluate alternatives and gain insight from past performance is the essence of marketing analytics. The course is focused on the marketing research decisions facing product managers in technology based companies and will appeal to students who want to gain a deeper understanding of such topics as the problems of target market selection, new product introductions, pricing, and customer retention. While the specifics of market analytics can vary across industries and firms, three main commonalities are: (1) defining the decision problem, (2) collection and analysis of high quality market data, and (3) implementing strategy through marketing mix decisions. In this course students will develop an understanding of available marketing analytic methods and the ability to use marketing research information to make strategic and tactical decisions.
**Course Learning Outcomes**

- Define the decision problem and determine what information is needed.
- Acquire trustworthy and relevant data and judge its quality.
- Develop an understanding of key modeling techniques.
- Utilize a modeling approach to be able to make certain types of marketing decisions.

**EBGN572. INTERNATIONAL BUSINESS STRATEGY. 3.0 Semester Hrs.**
The purpose of this course is to gain understanding of the complexities presented by managing businesses in an international environment. International business has grown rapidly in recent decades due to technological expansion, liberalization of government policies on trade and resource movements, development of institutions needed to support and facilitate international transactions, and increased global competition. Due to these factors, foreign countries increasingly are a source of both production and sales for domestic companies.

**EBGN575. ADVANCED MINING AND ENERGY ASSET VALUATION. 3.0 Semester Hrs.**
(I) The use of option pricing techniques in mineral and energy asset valuation. Mining and energy valuation standards and guidelines. Differentiation between static decision making, intertemporal decision making, and dynamic decision making under uncertainty. The comparison sales and cost approaches to valuation. Commodity price simulation and price forecasting. Risk-neutral valuation. Prerequisites: EBGN504, EBGN509, EBGN510, EBGN511, EBGN521, EBGN590. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- n/a

**EBGN576. MANAGING AND MARKETING NEW PRODUCT DEVELOPMENTS. 3.0 Semester Hrs.**
(II) This course provides a scientific approach to developing and marketing new products which are often critical to the success of firms competing in technology based industries. We will start with an overview of core marketing and then develop prototypes of a new product design. We will step through the new product development process in detail, learning about available tools and techniques to execute each process step along the way. New product prototypes will be used to gather data from prospective target markets and assess the viability of the design in the marketplace. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Use nimble processes to develop a new offering.
- Leverage your organization's resources, capabilities and technical opportunites.
- Formulate a vision for your proposed offering.
- Strategically segment and target the most promising beneficiaries.
- Gather, analyze and operationalize target segment(s) unmet needs and wants.
- Develop an innovative business model to ensure the new offering achieves its strategic objectives.
- Efficiently validate assumptions, features and customer acceptance of proposed offering.

- Create a plan to pilot your proposed offering and explore partnerships.
- Create an effective launch model/plan to maximize initial adoption of your proposed offering.

**EBGN577. LEADING & MANAGING HIGH PERFORMING TEAMS. 3.0 Semester Hrs.**
(I) Effective leaders contribute significantly to their organization's performance. When they take advantage of a technological innovation or respond to a crisis, leaders rely on critical skills to communicate their vision and coordinate tasks performed by others. This course is about developing your unique leadership skills and style whether you lead a small engineering team or, eventually, a large global corporation. We review key theories of leadership and examine the lessons learned from those who applied them. We synthesize and translate these lessons into specific behaviors that enhance your ability to lead. We discuss how generational shifts, economic and political factors impact the workplace in ways that call for effective, quality leadership. Ultimately, you have to understand how to lead and motivate individuals who don't look or think like you. This may involve motivating followers and involving them in making decisions. Following a learning-by-doing approach, we complement class discussions and case studies with a hands-on simulation of a leadership team facing a series of crises.
**Course Learning Outcomes**

- Articulate a vision of effective leadership that is refined across the course through participation in simulations, reflections and discussions.
- Assess the value of collaborative relationships, conflict resolution and human capital via case study analysis and discussions.
- Develop awareness of your leadership skills through individual and team leadership and personality assessments.
- Apply individual leadership skills in the context of organizational change through a variety of individual and team assessments, along with group discussions and simulations.
- Develop a plan based on best practices in effective leadership for organizational change to address the needs and challenges as identified in simulations.
- Distinguish between the roles of leaders versus managers within various case studies and course readings.
- Develop viable solutions that influence, motivate, and empower others through case study analysis and discussions.
- Analyze leadership styles and the necessary organizational conditions to foster team success using a variety of frameworks.

**EBGN578. BUSINESS OPERATIONS AND SUPPLY CHAIN MANAGEMENT. 3.0 Semester Hrs.**
Business Operations and Supply Chain Management is an elective course for ETM, approved masters and undergrad students who wish to learn how businesses operations support the business strategy. This course focuses on business operations for manufacturing and service industries, as well as Supply Chain Management. Students will gain an understanding of the businesses that they will shortly be involved with as they start their first career positions. Hands-on exercises to learn how to design processes, trouble shoot operational problems with root cause analysis, prepare business case studies, and conduct process simulations during the course. Key Business Operations topics include: operations strategy and objectives, product design, manufacturing production types, Lean Manufacturing, distribution, process design, productivity, optimization, control system theory, quality control, Total Quality Management (TQM), forecasting, and Six Sigma. Key Supply Chain Management topics include: capacity and demand planning, inventory management, distribution strategies, supplier risk mitigation and global supply chain management.
**Course Learning Outcomes**

- Design a dual-cycle value chain for a restaurant business with a diagram and 2-3 page report.
- Understand a variety of value-adding business models and their associated operations.
- Evaluate the impact of critical driving forces on the business' operations and supply chains through analysis and class discussions of case studies of technology startups.
- Define the business, sales and production strategies for an existing corporation in a 4-6 page paper.
- Create a detailed process flow diagram of value chain based on a real-world business operation.
- Analyze a quality control system using statistical process control through case studies and 3 homework quizzes.
- Validate organizational efficiency improvement measures, such as Control Systems, Total Quality Management, Six Sigma, Lean Manufacturing, and Sales Forecasting through a Mid-Term exam.
- Define the fundamental concepts and strategies of supply chain management through reading assignments and 3 homework quizzes.
- Manage a multi-tiered supply chain in a group of four students using two simulation games.

**EBGN580. EXPLORATION ECONOMICS. 3.0 Semester Hrs.**
Exploration planning and decision making for oil and gas, and metallic minerals. Risk analysis. Historical trends in exploration activity and productivity. Prerequisites: EENG480 or instructor consent.

**EBGN585. ENGINEERING AND TECHNOLOGY MANAGEMENT CAPSTONE. 3.0 Semester Hrs.**
This course represents the culmination of the ETM Program. This course is about the strategic management process ? how strategies are developed and imple mented in organizations. It examines senior management's role in formulating strategy and the role that all an organization's managers play in implementing a well thought out strategy. Among the topics discussed in this course are (1) how different industry conditions support different types of strategies; (2) how industry conditions change and the implication of those changes for strategic management; and (3) how organizations develop and maintain capabilities that lead to sustained competitive advantage. This course consists of learning fundamental concepts associated with strategic management process and competing in a web-based strategic management simulation to support the knowledge that you have developed.
**Course Learning Outcomes**

- Assess a given firm's resources and potential sources of competitive advantage within a variety of industries through case analyses and simulation development.
- Deduce the underlying problems in a complex business scenario through case analyses and simulation development.
- Articulate the type of and difference between business-level strategies and corporate-level strategies through class/team interactions and quizzes.
- Create strategic options that a particular firm could pursue based on the analysis of the internal and external environment through case analyses and simulation development.

- Deconstruct a fi rm's potential business or corporate-level strategies down to the tactical level for implementation through case analyses and simulation development.
- Predict appropriate strategic results for a given company using an evaluation of the internal and external environments through case analyses and simulation development.
- Experiment with implementing tactical choices that influence a firm's success rate through simulations.
- Reflect on previous performance results within the simulationto see the best tactical choices to implement moving forward.

**EBGN590. ECONOMETRICS I. 3.0 Semester Hrs.**
(II) This course covers the statistical methods used by economists to estimate economic relationships and empirically test economic theories. Topics covered include hypothesis testing, ordinary least squares, specification error, serial correlations, heteroskedasticity, qualitative and limited dependent variables, time series analysis and panel data. Prerequisites: MATH111, MATH530, EBGN509. 3 hours lecture and discussion; 3 semester hours.

**EBGN594. TIME-SERIES ECONOMETRICS. 3.0 Semester Hrs.**
(II) This is a course in applied time-series econometrics. It covers contemporary approaches for interpreting and analyzing time-series economic data. Hypothesis testing and forecasting both receive attention. Topics include stochastic difference equations, applied forecasting, stationary univariate models, models with constant and time-varying variance, deterministic and stochastic trend models and associated unit root and structural break tests, as well as single-equation and multiple-equation time-series models that include error-correction techniques and cointegration tests. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- No changes

**EBGN598. SPECIAL TOPICS IN ECONOMICS AND BUSINESS. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**EBGN598. SPECIAL TOPICS IN ECONOMICS AND BUSINESS. 0-6 Semester Hr.**

**EBGN598. SPECIAL TOPICS. 0-6 Semester Hr.**

**EBGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: "Independent Study" form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**EBGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

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**EBGN610. ADVANCED NATURAL RESOURCE ECONOMICS. 3.0 Semester Hrs.**
Optimal resource use in a dynamic context using mathematical programming, optimal control theory and game theory. Constrained optimization techniques are used to evaluate the impact of capital constraints, exploration activity and environmental regulations. Offered when student demand is sufficient. Prerequisites: Principles of Microeconomics, MATH111, MATH5301, EBGN509, EBGN510, EBGN511.

**EBGN611. ADVANCED MICROECONOMICS. 3.0 Semester Hrs.**
A second graduate course in microeconomics, emphasizing state-of-the-art theoretical and mathematical developments. Topics include consumer theory, production theory and the use of game theoretic and dynamic optimization tools. Prerequisites: Principles of Microeconomics, MATH111, MATH5301, EBGN509, EBGN511.

**EBGN632. PRIMARY FUELS. 3.0 Semester Hrs.**
(II) Application of models to understand markets for oil, gas, coal exploration and extraction. Empirical, theoretical and quantitative models and modeling techniques are stressed. The issues included are identification of cause and effect, market structure, game theory, futures markets, environmental issues, energy policy, energy regulation. The emphasis in the course is on the development of appropriate models and their application to current issues in primary fuel/upstream markets. Prerequisites: EBGN590. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- 1. Rigorous identification of issues affecting coal, oil and gas extraction
- 2. Market structure effects on production
- 3. The impact of policies on production and investment
- 4. Where to find basic data on energy supply and investment
- 5. How to organize basic information in a paper/presentation
- 6. How to write/present your thoughts in a clear and concise manner

**EBGN645. COMPUTATIONAL ECONOMICS. 3.0 Semester Hrs.**
(II) This course is about learning the skills required to construct and manipulate numerical models as an instrument of economic research. In the first part of the course, students will learn about basic classes of optimization problems as ways to operationalize models of equilibrium behavior from economics and how to formulate and solve these problems on the computer. In the second part of the course, students will focus on the techniques used specifically in computable general equilibrium (CGE) analysis and developing applications of CGE models to topics in energy,

environmental and natural resource economics. Prerequisites: MATH111, MATH530, Principles of Microeconomics, EBGN509, EBGN511. 3 hours lecture; 3 semester hours.

**Course Learning Outcomes**

- Understand basic classes of mathematical programming problems.
- Formulate and solve economic models on the computer.
- Calibrate numerical models for quantitative economic analysis.

**EBGN655. ADVANCED LINEAR PROGRAMMING. 3.0 Semester Hrs.**
Equivalent with EBGN650,
As an advanced course in optimization, this course will expand upon topics in linear programming. Specific topics to be covered include advanced formulation, column generation, interior point method, stochastic optimization, and numerical stability in linear programming. Applications of state-of-the-art hardware and software will emphasize solving real-world problems in areas such as mining, energy, transportation and the military. Prerequisites: EBGN555. 3 hours lecture; 3 semester hours.

**EBGN690. ECONOMETRICS II. 3.0 Semester Hrs.**
A second course in econometrics. Compared to EBGN590, this course provides a more theoretical and mathematical understanding of econometrics. Matrix algebra is used and model construction and hypothesis testing are emphasized rather than forecasting. Prerequisites: Principles of Microeconomics, MATH111, MATH530, EBGN509, EBGN590. Recommended: EBGN511.

**EBGN695. RESEARCH METHODOLOGY. 3.0 Semester Hrs.**
Lectures provide an overview of methods used in economic research relating to EPP and QBA/OR dissertations in Mineral Economics and information on how to carry out research and present research results. Students will be required to write and present a research paper that will be submitted for publication. It is expected that this paper will lead to a Ph.D. dissertation proposal. It is a good idea for students to start thinking about potential dissertation topic areas as they study for their qualifier. This course is also recommended for students writing Master's thesis or who want guidance in doing independent research relating to the economics and business aspects of energy, minerals and related environmental and technological topics. Prerequisites: MATH530, EBGN509, EBGN510, EBGN511, EBGN590.

**EBGN698. SPECIAL TOPICS IN ECONOMICS AND BUSINESS. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**EBGN698. SPECIAL TOPICS. 0-6 Semester Hr.**

**EBGN699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: "Independent Study" form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**EBGN707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.**
(I, II, S) Research credit hours required for completion of a Masters-level thesis or Doctoral dissertation. Research must be carried out under the direct supervision of the student's faculty advisor. Variable class and semester hours. Repeatable for credit.

## Professor

Jared C. Carbone

## Research Professor

Roderick G. Eggert

## Associate Professors

Benjamin Gilbert

Ian Lange

Steven Smith

## Assistant Professors

Maxwell Brown

Hojun Choi

## Teaching Professors

Scott Houser, Department Head

Becky Lafrancois

## Teaching Associate Professors

Crystal Dobratz

Michael Helwig

Sheron Lawson

Andrew Pederson

Jeremy Suiter

## Professor of Practice

Thomas Brady

David Culbreth

Daniel Jerrett

Patrick Leach

Paul Zink

## Professors Emeriti

Carol A. Dahl

Graham Davis

Franklin J. Stermole

John E. Tilton

Michael R. Walls

# Engineering, Design and Society

## Degrees

- Master of Science in Humanitarian Engineering and Science (thesis and non-thesis options)
- Graduate Certificate in Humanitarian Engineering and Science

## Program Description

The mission of the Department of Engineering, Design, and Society (EDS) is to engage in research, education, and outreach that inspires and empowers engineers and applied scientists to become innovative and impactful leaders in socio-technical design, problem definition, and problem solution. Our graduates are prepared to address the challenges of attaining a thriving, sustainable global society. Humanitarian Engineering and Science (HES) is a set of graduate program offerings within EDS.

HES connects students with a passion for contributing to social and environmental problem solving to Mines faculty who lead the field of applying engineering to pressing social, environmental, and community challenges. Integrating engineering with social sciences and design, HES offers courses that teach students how to work *with* the communities they seek to serve by co-creating solutions that promote justice, responsibility, and sustainability. HES serves students who have diverse career goals spanning NGOs, government agencies and research groups, start-ups, and established companies. Seminar-style courses offered by EDS, along with selected technical courses offered by other academic units across campus, provide students a balance of breadth and depth in applying engineering to social, environmental, and community challenges.

Information on the Humanitarian Engineering and Science degree programs can be found in the Interdisciplinary Programs section of the catalog.

Courses

**EDNS501. COMMUNITY-CENTERED APPROACHES TO RESILIENCE. 3.0 Semester Hrs.**
Community resilience to the inevitable effects of a changing climate is an emmerging topic in local and global community development spheres. This course will provide learners with a survey of how institutions from governments, donors, to public and private organizations are quickly pivoting from a world of ‘sustainable development goals’ to one of resilience, remediation, and adaptation at national, subnational, and local scales, and how sociotechnical perspectives can support their participation in this new world. At the end of this eight-week course, learners will be able to assess and answer the following questions: [1] what is 'community resilience' and how do different communities, stakeholders, and sectors define it, [2] how does new terminology around ‘resilience’ relate to previous humanitarian efforts aimed at sustainable community development, [3] what are significant sociotechnical pillars of resilience, including built infrastructure and the environment, social infrastructure and governance, [4] how can mainstream efforts aimed at resilience lead to inequality and perpetuate systemic power imbalance. Experiential learning through guest speakers and case studies will illuminate the varied and multidimensional and intersectional aspects of resilience.
**Course Learning Outcomes**

**EDNS502. MANAGING AND LEADING IN MULTISTAKEHOLDER ENVIRONMENTS. 3.0 Semester Hrs.**
Managing, leading, and dare we say ‘solving’ wicked public interest issues requires multistakeholder engagement across sectors, agencies, and public interest domains. This course is designed to provide learners with tools to manage and lead across these complex multistakeholder environments, and to navigate wicked problems, like climate change and community resilience. This course is designed for those who are or aspire to be public-facing managers and leaders—including those working for state and federal agencies, nonprofits, non-governmental organizations (NGOs), and quasi-governmental organizations. Key learning objectives include [1] defining the public interest, [2] assessing stakeholder environments, [3] exploring ethical decision-making tools and considering competing stakeholder interests, [4] analyzing the functions and roles of the ‘responsible’ public manager, [5] synthesizing modern community-engaged leadership styles and applying them in practice, [6] exploring current challenges and perspectives from leaders in relevant fields and organizations, and [6] learning and applying advanced communication skills.
**Course Learning Outcomes**

**EDNS515. INTRODUCTION TO SCIENCE AND TECHNOLOGY STUDIES. 3.0 Semester Hrs.**
This course engages scholarship on the inextricable link between science, engineering and the various social contexts within which scientists and engineers work. We begin by critically reflecting on the question, What are science and engineering for? We then explore key conceptual domains in the social scientific study of science and engineering, including knowledge, agency, and expertise. We will learn from a diverse set of social scientific experts who study and collaborate with scientists and engineers. Students will leave the course with a better understanding of how social scientific inquiry can aid in understanding, and practicing, science and engineering. They will also have a clearer articulation of their individual professional commitments and how those fit with more traditional understandings of science and engineering.
**Course Learning Outcomes**

- By the end of this course, students will have demonstrated the ability to:
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**EDNS544. INNOV8X. 3.0 Semester Hrs.**
Innov8x introduces concepts and tools to accelerate the design, validation and adoption of innovations in support of creative problem solving. Using an entrepreneurial mindset, we learn how to identify and frame problems that beneficiaries and stakeholders face. We attempt to design and test practical solutions to those problems in collaboration with those who experience the problems. We apply beneficiary discovery, pretotyping, business model design (social, economic and environmental), constrained creativity, efficient experimentation, and rapid iteration. While resolving challenges involves technical solutions, an important aspect of this course is directly engaging beneficiaries and stakeholders in social contexts to develop solutions with strong impact potential. Innov8x is grounded in collaborative creativity theory

at the intersection of organizational behavior (social psychology), design principles, entrepreneurship and innovation management.
**Course Learning Outcomes**

- Frame and translate complex ambiguous problems into actionable opportunities for innovation
- Conduct effective, objective and ongoing beneficiary discovery in efficient ways
- Combine tools and methods to quickly test assumptions and secure beneficiary acceptance
- Develop creative approaches to navigate real and perceived constraints
- Leverage mentor and stakeholder support through credible communication based on research • Launch innovative solutions with the advocacy of beneficiaries and stakeholders
- Create value by solving complex problems that straddle technical and social domains
- Launch innovative solutions with the advocacy of beneficiaries and stakeholders

**EDNS577. ADVANCED ENGINEERING AND SUSTAINABLE COMMUNITY DEVELOPMENT. 3.0 Semester Hrs.**
Analyzes the relationship between engineering and sustainable community development (SCD) from historical, political, ethical, cultural, and practical perspectives. Students will study and analyze different dimensions of sustainability, development, and "helping", and the role that engineering might play in each. Will include critical explorations of strengths and limitations of dominant methods in engineering problem solving, design and research for working in SCD. Through case-studies, students will analyze and evaluate projects in SCD and develop criteria for their evaluation. 3 hours lecture and discussion; 3 semester hours.
**Course Learning Outcomes**

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**EDNS578. ENGINEERING AND SOCIAL JUSTICE. 3.0 Semester Hrs.**
Equivalent with LAIS578,
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**EDNS579. COMMUNITY-BASED RESEARCH METHODS. 3.0 Semester Hrs.**
Engineers and applied scientists face challenges that are profoundly sociotechnical in nature, and communities are increasingly calling for greater participation in the decisions that affect them. Understanding the diverse perspectives of communities and being able to establish positive working relationships with their members is therefore crucial to the socially responsible practice of engineering and applied science. This course provides graduate students with the conceptual and methodological tools to conduct community-based research. Graduate students will learn ethnographic field methods and participatory research strategies, and critically assess the strengths and limitations of these through a final original research project related to their ongoing independent research or practicums.
**Course Learning Outcomes**

- During this course students will learn to:

**EDNS580. HUMANITARIAN ENGINEERING AND SCIENCE CAPSTONE PRACTICUM. 3.0 Semester Hrs.**
(I, II, S) This course allows students to practice the concepts, theories and methods learned in HES courses with the goal of making relevant their academic training to real world problems. This practicum can be achieved through a number of possibilities approved by HES director, including supervision and/or shadowing in HES-related activities, engaging in a social enterprise where they do problem definition, impact gap analysis and layout a business canvas, and designing and carrying out a project or fieldwork of their own, etc. Prerequisite: EDNS570, EDNS479. 3 hours research; 3 semester hours.
**Course Learning Outcomes**

- • Identify successful practices for humanitarian projects in real settings (ABET a,h,j) • Determine different ways in which previous humanitarian projects could have been improved to yield more successful technical and social results (ABET a,b,h,j) • Determine effective engineering methods for different humanitarian applications (ABET b,c,h,j) • Work in teams to design, execute and evaluate a project with stakeholders (ABET a,b,c,d,e,j,k) • Gain experience in engaging and communicating with community members and stakeholders (ABET c,d,f,h,i,j,k) • Develop stronger professional communication skills through written assignments, group projects, discussions, presentations, and community engagement (ABET g,f,h,i,j,k)

**EDNS590. RISKS IN HUMANITARIAN ENGINEERING AND SCIENCE. 3.0 Semester Hrs.**
(I) This course provides students with opportunities to consider the risks related to humanitarian projects—or any projects that effect and involve people. These risks might include things that different scientific and engineering disciplines typically consider, as well as those that may be pertinent to project stakeholder perspectives. Guided by social scientific insights related to risk, students in this class will gain new tools for defining problems in ways that are relevant and appropriate for multiple contexts. Students will read, discuss, and analyze material together and to undertake independent research to deepen their understandings of chosen topics. 3 semester hours.
**Course Learning Outcomes**

- • Analyze humanitarian science and engineering projects using established evaluation criteria (ABET a,h,j) • Identify the most successful practices for humanitarian science and engineering (ABET a,h,j) • Determine different ways in which previous engineering or scientific projects could have been improved to yield more successful technical and social results (ABET a,b,h,j) • Gain conceptual tools for and experience in engaging and communicating with community members and stakeholders (ABET c,d,f,h,i,j,k) • Develop stronger professional communication skills through written assignments, group projects, discussions, presentations, and community engagement (ABET g,f,h,i,j,k)

**EDNS597. SUMMER PROGRAMS. 0-6 Semester Hr.**

**EDNS598. SPECIAL TOPICS IN ENGINEERING DESIGN & SOCIETY. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**EDNS598. SPECIAL TOPICS. 0-6 Semester Hr.**

**EDNS598. SPECIAL TOPICS. 0-6 Semester Hr.**

**EDNS599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Variable credit: 0.5 to 6 credit hours.

Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree. Independent Study form must be completed and submitted to the Registrar.
**Course Learning Outcomes**

**EDNS707. GRADUATE THESES. 1-15 Semester Hr.**

## Department Leadership

Dean Nieusma, Department Head

Chelsea Salinas, Assistant Department Head; Director of Design Engineering Program

## Professors

Juan Lucena, Humanitarian Engineering Director of Undergraduate Programs and Outreach

Kevin Moore, Executive Director of Humanitarian Engineering

Jessica Smith

## Assistant professors

Elizabeth Reddy, Assistant Director of Humanitarian Engineering and Science Interdisciplinary Graduate Program

Marie Stettler Kleine

## Teaching Professors

Yosef Allam, Director of Cornerstone Design Program

Alina Handorean

## Teaching Associate Professors

Jack Bringardner

Mirna Mattjik

Mark Orrs

Sid Saleh, Director of McNeil Center for Entrepreneurship & Innovation

Kate Youmans, Presidential Faculty Fellow for Diversity, Inclusion & Access

## Teaching Assistant Professors

Cynthia Athanasiou

Duncan Davis-Hall

Michael Sheppard

Aubrey Wigner

## Professors of Practice

Donna Bodeau

Garrett Erickson

Antonie Vandenberge

## Staff

Becky Buschke, Program Assistant

Leah Fitzgerald, Stakeholder Relations Manager

Kirsten Kelly, Capstone Administrative Assistant

Julia Roos, Associate Director of Humanitarian Engineering

Kimberly Walker, Department Manager

# Electrical Engineering

## Degrees Offered

- Professional Online Masters in Electrical Engineering *This degree can be earned by completing the last three certificates listed below plus one additional course.
- Master of Science (Electrical Engineering)
- Doctor of Philosophy (Electrical Engineering)
- Graduate Certificate in Data Science for Signals and Systems
- Graduate Certificate in Information and Systems Sciences
- Graduate Certificate in Microwave Engineering
- Graduate Certificate in Power and Energy Systems

## Program Overview

The Electrical Engineering Department offer the degrees Master of Science and Doctor of Philosophy in Electrical Engineering. These degree programs demand academic rigor and depth yet also address real-world problems.

The Department has three areas of research activity that stem from the core fields of Electrical Engineering: 1) Antennas and Wireless Communications, 2) Information and Systems Science, and 3) Power and Energy Systems. Individual research projects may encompass more than one research area.

## Research Areas:

***Antennas and Wireless Communications*** is a research area that builds on the fundamental physics and mathematics of electromagnetic waves and propagation. The research in this area includes design, analysis, optimization, and measurement of antennas, antenna arrays, microwave, millimeter-wave, and terahertz devices. Applications address current academic, industry, and society needs, such as wireless communication systems, radar and remote sensing, and electromagnetic imaging.

***Information and Systems Sciences*** is an interdisciplinary research area that encompasses the fields of control systems, data science, optimization, signal and image processing, compressive sensing, robotics, and mechatronics. Applications can be found in renewable energy and power systems, materials processing, sensor and control networks, bio-engineering, computer vision and pattern recognition, autonomous systems, imaging, intelligent structures, and geosystems.

***Power and Energy Systems*** is focused on both fundamental and applied research in the interrelated fields of conventional electric power systems and electric machinery, renewable energy and distributed generation, energy economics and policy issues, power quality, power electronics and drives. The overall scope of research encompasses a broad spectrum of electrical energy applications including investor-owned

utilities, rural electric associations, manufacturing facilities, regulatory agencies, and consulting engineering firms.

## Program Details

The Electrical Engineering Department offers the degrees Master of Science and Doctor of Philosophy in Electrical Engineering. The master's program is designed to prepare candidates for careers in industry or government or for further study at the PhD level; both thesis and non-thesis options are available. The PhD degree program is sufficiently flexible to prepare candidates for careers in industry, government, or academia. See the information that follows for full details on these four degrees.

## Mines Combined Undergraduate/Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework (500-level) to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

## Prerequisites

*Requirements for Admission to EE:* The minimum requirements for admission to the MS and PhD degrees in Electrical Engineering are:

- A baccalaureate degree in engineering, computer science, a physical science, or math with a grade-point average of 3.0 or better on a 4.0 scale.
- TOEFL score of 79 or higher (or 550 for the paper-based test or 213 for the computer-based test) for applicants whose native language is not English. In lieu of a TOEFL score, an IELTS score of 6.5 or higher will be accepted.
- For the PhD program, prior research experience is desired but not required.

*Admitted Students:* The EE department graduate committee may require that an admitted student take undergraduate remedial coursework to overcome technical deficiencies. The committee will decide whether to recommend regular or provisional admission.

*Transfer Courses:* Graduate-level courses taken at other universities for which a grade equivalent to a B or better was received will be considered for transfer credit with approval of the advisor and/or thesis committee, and EE department head, as appropriate. Transfer credits must not have been used as credit toward a bachelor's degree. For the MS degree, no more than 9 credits may transfer. For the PhD degree, up to 24 credits may be transferred. In lieu of transfer credit for individual courses, students who enter the PhD program with a thesis-based master's degree from another institution may transfer up to 36 hours in recognition of the coursework and research completed for that degree.

*Advisor and Thesis Committee:* Students must have an advisor from the EE faculty to direct and monitor their academic plan, research, and independent studies. Advisors must be full-time permanent members of the faculty. In this context, full-time permanent members of the faculty are those that hold the rank of professor, associate professor, assistant professor, research professor, associate research professor or assistant research professor. Upon approval by the graduate dean, adjunct faculty, teaching faculty, visiting professors, emeritus professors and off-campus representatives may be designated additional co-advisors. A list of EE faculty by rank is available in the faculty tab in the catalog.

Master of Science (thesis option) students must have at least three members on their thesis committee; the advisor and one other member must be permanent faculty in the EE department. Students who choose to have a minor program must select a representative from the minor area of study to serve on the thesis committee.
PhD thesis committees must have at least four members; the advisor and two additional members must be permanent faculty in the EE department, and one member must be outside the departmental faculty and serving as chair of the committee. Students who choose to have a minor program must select a representative from the minor area of study to serve on the thesis committee.

*Degree Audit and Admission to Candidacy:* All degree students must submit required forms by the deadlines posted by the Office of Graduate Studies

Master's thesis students must complete the Degree Audit form by the posted deadline.
PhD students need to submit the Degree Audit form by the posted deadline and need to submit the Admission to Candidacy form by the first day of the semester in which they want to be considered eligible for reduced registration.

*Time Limit:* As stipulated by the Mines Graduate School, a candidate for a master's degree must complete all requirements for the degree within five years of the date of admission into the degree program. A candidate for a doctoral degree must complete all requirements for the degree within nine years of the date of admission into the degree program.

## Program Requirements

## Master of Science – Electrical Engineering

The MS degree in Electrical Engineering (thesis or non-thesis Option) requires 30 credits. All MS students are also required to enroll in the zero-credit course EENG 500 Graduate Seminar each semester . Requirements for the thesis MS are 24 hours of coursework and 6 credits of thesis research. The non-thesis option requires 30 credits of coursework. A maximum of 6 credits of independent study can be used to fulfill degree requirements. There are three tracks in Electrical Engineering: 1) Antennas and Wireless Communications (AWC), 2) Power and Energy Systems (PES), and 3) Information and Systems Sciences (ISS). Students are encouraged to decide between tracks before pursuing an advanced degree. Students are also encouraged to speak to their advisor and/or a member of the EE faculty before registering for classes and to select a permanent advisor as soon as possible. The following set of courses is required of all students.

## MS Thesis - Electrical Engineering

| | | |
|---|---|---|
| EENG707 | GRADUATE THESIS / DISSERTATION RESEARCH CREDIT | 6.0 |
| EENG500 | ELECTRICAL ENGINEERING SEMINAR (All tracks) Enrollment required every fall and spring semester | 0.0 |
| EE CORE: EE Core Courses (AWC track) | | 9.0 |
| EE CORE: EE Core Courses (PES track) | | 0.0 |
| EE CORE: EE Core Courses (ISS track) | | 12.0 |

| | | |
|---|---|---|
| TECHNICAL ELECTIVES | Technical Electives must be approved by Thesis Committee | |
| AWC Technical Electives | | 15.0 |
| PES Technical Electives | | 24.0 |
| ISS Technical Electives | | 12.0 |

*MS Thesis Defense:* At the conclusion of the MS (thesis option), the student will be required to make a formal presentation and defense of her/his thesis research.

## MS Non-Thesis - Electrical Engineering

| | | |
|---|---|---|
| EENG500 | ELECTRICAL ENGINEERING SEMINAR (All tracks) Enrollment required every fall and spring semester | 0.0 |
| EE CORE: EE Core Courses (AWC track) | | 9.0 |
| EE CORE: EE Core Courses (PES track) | | 0.0 |
| EE CORE: EE Core Courses (ISS track) | | 12.0 |
| TECHNICAL ELECTIVES | Technical Electives must be approved by Advisor | |
| AWC Technical Electives | | 15.0 |
| PES Technical Electives | | 24.0 |
| ISS Technical Electives | | 12.0 |
| EE Electives (all tracks) | Must be taught by an EE graduate faculty or approved by Advisor | 6.0 |

## Doctor of Philosophy - Electrical Engineering

The PhD degree in Electrical Engineering requires 72 credits of coursework and research credits. A minimum of 30 credits of coursework and a minimum of 24 credits of research is required. The remaining 18 credits required can be earned through research or coursework and students should consult with their advisor and/or thesis committee. The students are also required to enroll in the zero-credit course EENG 500 Graduate Seminar each semester. There are three tracks in Electrical Engineering: 1) Antennas and Wireless Communications (AWC), 2) Power and Energy Systems (PES), and 3) Information and Systems Sciences (ISS). Students are encouraged to decide between tracks before pursuing an advanced degree. Students are also encouraged to speak to their advisor and/or a member of the EE faculty before registering for classes and to select a permanent advisor as soon as possible. The following set of courses is required of all students.

| | | |
|---|---|---|
| EENG707 | GRADUATE THESIS / DISSERTATION RESEARCH CREDIT | 24.0 |
| EENG500 | ELECTRICAL ENGINEERING SEMINAR (All tracks) Enrollment required every fall and spring semester | 0.0 |
| EE CORE: EE Core Courses (AWC track) | | 9.0 |
| EE CORE: EE Core Courses (PES track) | | 0.0 |
| EE CORE: EE Core Courses (ISS track) | | 12.0 |
| EE Technical Electives | Technical Electives must be approved by Thesis Committee | |
| AWC Technical Electives | | 27.0 |
| PES Technical Electives | | 36.0 |
| ISS Technical Electives | | 24.0 |

## PhD Qualifying Examination

Students wishing to enroll in the Electrical Engineering PhD program will be required to pass a qualifying exam. Normally, full-time PhD candidates will take the qualifying exam in their first year, but it must be taken within four semesters of entering the program. Part-time candidates will normally be expected to take the qualifying exam within no more than six semesters of entering the program.

The purpose of the qualifying exam is to assess some of the attributes expected of a successful PhD student, including:

- To determine the student's ability to review, synthesize and apply fundamental concepts.
- To determine the creative and technical potential of the student to solve open-ended and challenging problems.
- To determine the student's technical communication skills.

Students will be asked to prepare an oral presentation to be given to the Qualifying Exam Committee. This will be a technical presentation (typically 30-45 minutes) on a topic chosen by the student's advisor in consultation with the student. It could cover a single paper from the literature, a number of papers on a common subject, or a specific topic for which the student would need to perform a literature review. The topic may or may not be directly related to the student's research area.

Through this presentation, the student is expected to give a clear problem statement, technical insight, and critical analysis of the topic. In addition, he/she may be asked to show her/his understanding of the physics and mathematics behind the broad topic of the presentation. As a rule of thumb, it is expected that the student spends one to two months to prepare for the oral part of the Qualifying Exam. As such, all applicants are encourage to discuss the oral presentation with their advisors well in advance.

### Final pass/fail decision

Based on the oral presentation, the Qualifying Exam Committee will determine whether the student has passed the exam. Official results will be communicated to the student typically by the end of the summer semester. This date could change depending on the completion date of the oral exam. When appropriate and desirable, the Qualifying Exam Committee may ask the student for additional coursework requirements and/or other remedial action.

In the event of a student failing the Qualifying Exam, he/she will be given one further opportunity to pass the exam in the following spring semester. If a second failure occurs, the student has unsatisfactory academic performance that results in an immediate mandatory dismissal of the graduate student from the PhD program.

## PhD Thesis Proposal

After passing the qualifying exam, the PhD student is allowed up to 18 months to prepare a written thesis proposal and present it formally to the student’s graduate committee and other interested faculty.

*Admission to Candidacy:* In addition to the Graduate School requirements, full-time students must complete the following requirements within two calendar years of enrolling in the PhD program.

- Have a thesis committee appointment form on file in the Graduate Office:
- Have passed the PhD qualifying exam demonstrating adequate preparation for, and satisfactory ability to conduct doctoral research.

## PhD Thesis Defense

At the conclusion of the student’s PhD program, the student will be required to make a formal presentation and defense of her/his thesis research. The EE department enforces a defense policy for PhD students

with regards to their publications and presentations. According to this policy, the required and recommended publications and presentations for EE PhD students before graduation are listed below:

- Journal Publications
  - Required: Minimum of one first-author paper accepted or published in a peer-reviewed journal before the dissertation defense.
  - Recommended: Three or more first-author papers accepted or published in peer-reviewed journals. More than three first-author journal publications are recommended for students interested in academic positions.
- Presentations
  - Required: Minimum of one research presentation (poster or oral presentation) before the dissertation defense. Possible venues include an external technical conference, the campus-wide graduate student research conference, the departmental colloquium, or a sponsor meeting.
  - Recommended: Two or more research presentations at external technical conferences where the student is the first author on the presented work. Numerous conference presentations are strongly encouraged to establish a research reputation for students interested in academic positions.
- Exceptions: Students wanting to defend before meeting these requirements must submit a one-page petition with reasonable explanation to the EE graduate committee. Certain conferences, particularly some related to Computer Science, publish longer papers and have high standards for acceptance and thus may be considered as journal-quality. Finally, while some journals may have lengthy review timelines and thus some students may wish to defend their dissertation while a journal paper is still under review, students should be aware that peer review comments and final decisions provide valuable input to a dissertation committee in assessing a student's research. Reviews from intermediate conference publications can help in assessing a recent journal submission.
- MS thesis students: It is recommended that students pursuing a thesis-based MS degree have submitted at least one paper to a peer-reviewed journal or conference and given at least one research presentation (poster or oral presentation) before the dissertation defense.

**Electrical Engineering Courses**

***Required Core: Antennas and Wireless Communications Track***

All students must take three of the following five core courses.

| | | |
|---|---|---|
| EENG525 | ANTENNAS | 3.0 |
| EENG526 | ADVANCED ELECTROMAGNETICS | 3.0 |
| EENG527 | WIRELESS COMMUNICATIONS | 3.0 |
| EENG528 | COMPUTATIONAL ELECTROMAGNETICS | 3.0 |
| EENG530 | PASSIVE RF & MICROWAVE DEVICES | 3.0 |

***Required Core: Power and Energy Systems Track***

There is no core course requirement for the PES track.

***Required Core: Information and Systems Sciences Track***

All students must take:

| | | |
|---|---|---|
| EENG515 | MATHEMATICAL METHODS FOR SIGNALS AND SYSTEMS | 3.0 |

and choose at least three of the following:

| | | |
|---|---|---|
| EENG509 | SPARSE SIGNAL PROCESSING | 3.0 |
| EENG510 | ADVANCED DIGITAL SIGNAL PROCESSING | 3.0 |
| EENG511 | CONVEX OPTIMIZATION AND ITS ENGINEERING APPLICATIONS | 3.0 |
| EENG514 | DATA SCIENCE FOR ELECTRICAL ENGINEERING | 3.0 |
| EENG517 | THEORY AND DESIGN OF ADVANCED CONTROL SYSTEMS | 3.0 |
| EENG519 | ESTIMATION THEORY AND KALMAN FILTERING | 3.0 |
| EENG589 | DESIGN AND CONTROL OF WIND ENERGY SYSTEMS | 3.0 |

## Professional Online Masters in Electrical Engineering

The professional master's degree is designed to train and target recent graduates or mid-career professionals with a B.S. in electrical engineering or a related field in physics or applied sciences. The program is composed of 3 stackable certificates plus a required graduate-level mathematics course (MEGN502). To complete the professional master's degree the student must complete 30 credits as outlined below.

Students may also register for the professional masters at the outset and take a mixture of courses (from the tracks) in any order. Should the student elect to register for the full masters, then certificates will not be awarded on completion of the full degree. For these students, we refer to the certificates as 'tracks' as no certificates will be awarded.

### Certificate 1 / Track 1: Information and System Sciences – students must complete 9 hours of coursework as follows:

| | | |
|---|---|---|
| EENG510 | ADVANCED DIGITAL SIGNAL PROCESSING | 3.0 |
| EENG515 | MATHEMATICAL METHODS FOR SIGNALS AND SYSTEMS | 3.0 |
| EENG519 | ESTIMATION THEORY AND KALMAN FILTERING | 3.0 |

### Certificate 2 / Track 2 : Microwave Engineering – students must complete 9 hours of coursework as follows:

| | | |
|---|---|---|
| EENG529 | ACTIVE RF & MICROWAVE DEVICES | 3.0 |
| EENG530 | PASSIVE RF & MICROWAVE DEVICES | 3.0 |
| EENG532 | LOW TEMPERATURE MICROWAVE MEASUREMENTS FOR QUANTUM ENGINEERING | 3.0 |

### Certificate 3 / Track 3: Power & Energy Systems – students must complete 9 hours of coursework as follows:

| | | |
|---|---|---|
| EENG570 | ADVANCED HIGH POWER ELECTRONICS | 3.0 |
| EENG577 | ADVANCED ELECTRICAL MACHINE DYNAMICS FOR SMART-GRID SYSTEMS | 3.0 |

| | | |
|---|---|---|
| EENG585 | AI FOR POWER AND RENEWABLE ENERGY SYSTEMS | 3.0 |

While all courses are to be delivered online, students that are interested in attending an on-campus class, may substitute one of the above courses per each certificates (or track) with one of the with appropriate track electives as listed in our Graduate Catalog.

## Graduate certificate in information and system sciences

The post-baccalaureate certificate program in Information and System Sciences is targeted to train recent graduates or mid-career professionals with a basic knowledge of modeling and extracting information from signals, systems, or data sets.

To earn the post-baccalaureate certificate program in Information and System Sciences, students must complete 9 hours of coursework as follows:

Required Courses:

| | | |
|---|---|---|
| EENG510 | ADVANCED DIGITAL SIGNAL PROCESSING | 3.0 |
| EENG515 | MATHEMATICAL METHODS FOR SIGNALS AND SYSTEMS | 3.0 |
| EENG519 | ESTIMATION THEORY AND KALMAN FILTERING | 3.0 |

While all courses are to be delivered online, students that are interested in attending an on-campus class may substitute one of the above courses with one of the Information and Systems Sciences track electives as listed in our Graduate Catalog.

## Graduate certificate in microwave engineering

The online certificate program in Microwave Engineering is targeted to train recent graduates or mid-career professionals with a B.S. in electrical engineering or a related field in physics or applied sciences with a basic knowledge of electromagnetic theory, specifically for handling the challenges and demands of modern microwave systems.

To complete the online certificate program in Microwave Engineering, students must complete 9 hours of coursework as follows:

Required Courses:

| | | |
|---|---|---|
| EENG529 | ACTIVE RF & MICROWAVE DEVICES | 3.0 |
| EENG530 | PASSIVE RF & MICROWAVE DEVICES | 3.0 |
| EENG532 | LOW TEMPERATURE MICROWAVE MEASUREMENTS FOR QUANTUM ENGINEERING | 3.0 |

While all courses are to be delivered online, students that are interested in attending an on-campus class may substitute one of the above courses with one of the Antennas & Wireless electives as listed in our Graduate Catalog.

## graduate certificate in power and energy systems

The online certificate program in Power and Energy Systems is targeted to train recent graduates or mid-career professionals with a B.S. in electrical engineering or a related field in physics or applied sciences with a basic knowledge of power systems and machines.

To complete the online certificate program in Power and Energy Systems, students must complete 9 hours of coursework as follows:

Required Courses:

| | | |
|---|---|---|
| EENG570 | ADVANCED HIGH POWER ELECTRONICS | 3.0 |
| EENG577 | ADVANCED ELECTRICAL MACHINE DYNAMICS FOR SMART-GRID SYSTEMS | 3.0 |
| EENG585 | AI FOR POWER AND RENEWABLE ENERGY SYSTEMS | |

While all courses are to be delivered online, students that are interested in attending an on-campus class may substitute one of the above courses with one of the Power and Energy Systems electives as listed in our Graduate Catalog.

## Graduate Certificate in Data Science for Signals and Systems

The graduate certificate program in Data Science for Signals and Systems is targeted to train recent graduates or mid-career professionals with a BS in electrical engineering or a related field in mathematical and algorithmic aspects of data science relevant for electrical engineers, specifically for handling the signals and data that are processed and created by modern physical and virtual electrical systems.

To earn the graduate certificate in Data Science for Signals and Systems, students must complete 12 credits as follows:

***Required Courses:***

| | | |
|---|---|---|
| EENG514 | DATA SCIENCE FOR ELECTRICAL ENGINEERING | |
| EENG515 | MATHEMATICAL METHODS FOR SIGNALS AND SYSTEMS | 3.0 |

***Choose 2 out of 5:***

| | | |
|---|---|---|
| EENG509 | SPARSE SIGNAL PROCESSING | 3.0 |
| EENG511 | CONVEX OPTIMIZATION AND ITS ENGINEERING APPLICATIONS | 3.0 |
| EENG519 | ESTIMATION THEORY AND KALMAN FILTERING | 3.0 |
| EENG521 | NUMERICAL OPTIMIZATION | 3.0 |
| EENG586 | COMMUNICATION NETWORKS FOR POWER SYSTEMS | 3.0 |

# Courses

**EENG500. ELECTRICAL ENGINEERING SEMINAR. 0.0 Semester Hrs.**
This zero-credit graduate course builds on the EE department seminars in the colloquium series, which consist of presentations delivered by external or internal invited speakers on topics broadly related to electrical engineering. The seminar is mandatory for all graduate students (MS and Ph.D.). The students would need to enroll in the course every semester. Any student who cannot take the course for valid reasons should notify their adviser, who will then make a request to the EE graduate committee for a waiver. These requests could be for the duration of one semester or longer. The course will be graded as PRG/PRU based on student attendance at the department seminars in the colloquium series - the student has to attend at least two thirds of all the seminars each semester in order to get a PRG grade.
**Course Learning Outcomes**

- Graduates will demonstrate the ability to conduct directed research.
- Graduates will demonstrate oral and written communication skills.

**EENG507. INTRODUCTION TO COMPUTER VISION. 3.0 Semester Hrs.**
Equivalent with CSCI507,CSCI512,EENG512,
Computer vision is the process of using computers to acquire images, transform images, and extract symbolic descriptions from images. This course provides an introduction to this field, covering topics in image formation, feature extraction, location estimation, and object recognition. Design ability and hands-on projects will be emphasized, using popular software tools. The course will be of interest both to those who want to learn more about the subject and to those who just want to use computer imaging techniques.
**Course Learning Outcomes**

- 1. Be able to analyze and predict the behavior of image formation, transformation, and recognition algorithms.
- 2. Be able to design, develop, and evaluate algorithms for specific applications.
- 3. Be able to use software tools to implement computer vision algorithms.
- 4. Communicate (in oral and written form) methods and results to a technical audience.

**EENG509. SPARSE SIGNAL PROCESSING. 3.0 Semester Hrs.**
This course presents a mathematical tour of sparse signal representations and their applications in modern signal processing. The classical Fourier transform and traditional digital signal processing techniques are extended to enable various types of computational harmonic analysis. Topics covered include time-frequency and wavelet analysis, filter banks, nonlinear approximation of functions, compression, inverse problems, compressive sensing, and connections with machine learning. Offered Spring semester of even years. Prerequisites: EENG411 and EENG515 or instructor consent.
**Course Learning Outcomes**

- Students will develop the link between the Fourier, time-frequency, and wavelet transforms.
- Compute and analyze linear and nonlinear approximations of functions.
- Students will be able to use sparse signal representations for solving signal restoration and inverse problems.

**EENG510. ADVANCED DIGITAL SIGNAL PROCESSING. 3.0 Semester Hrs.**
Equivalent with CSCI510,EGGN510,
This course covers mathematical and engineering aspects of digital signal processing (DSP). An emphasis is placed on the various possible representations for discrete-time signals and systems (in the time, z-, and frequency domains) and how those representations can facilitate the identification of signal properties, the design of digital filters, and the sampling of continuous-time signals. Deterministic and random signal and noise models are discussed, as are methods for noise removal and power spectrum estimation. Additional topics include multi-rate signal processing and spectral analysis using the discrete Fourier transform. The course will be useful to all students who are concerned with information bearing signals and signal processing in a wide variety of application settings, including sensing, instrumentation, control, communications, signal interpretation and diagnostics, and imaging. Prerequisite: EENG310, EENG 311, EENG 391; or consent of instructor.
**Course Learning Outcomes**

- Design digital filters to particular specifications (passband, cutoff, order, etc.)
- Use digital filters to process analog signals (appreciating the roles of sampling, aliasing, digital filtering, sample rate conversion, and interpolation).
- Analyze the frequency spectrum of digital and sampled analog signals using windowing and the discrete Fourier transform (DFT).
- Estimate the power spectrum of random signals.
- Implement digital signal processing techniques in computational software.

**EENG511. CONVEX OPTIMIZATION AND ITS ENGINEERING APPLICATIONS. 3.0 Semester Hrs.**
The course focuses on recognizing and solving convex optimization problems that arise in applications in various engineering fields. Covered topics include basic convex analysis, conic programming, duality theory, unconstrained optimization, and constrained optimization. The application part covers problems in signal processing, power and energy, machine learning, control and mechanical engineering, and other fields, with an emphasis on modeling and solving these problems using the CVX package. Offered Spring semester of even years. Prerequisite: EENG515 or instructor consent.
**Course Learning Outcomes**

- Recognize convex optimization problems that arise in applications.
- Understand the basic theory of convex optimization.
- Understand how convex optimizations are solved and solve them using various free packages.
- Use convex optimization in their research work or applications.

**EENG514. DATA SCIENCE FOR ELECTRICAL ENGINEERING. 3.0 Semester Hrs.**
This course presents a comprehensive exposition of the theory, methods, and algorithms for data analytics as related to power and energy systems. It will focus on (1) techniques for performing statistical inference based on data, (2) methods for predicting future values of data, (3) methods for classifying data instances into relevant classes and clusters, (4) methods for building, training and testing artificial neural networks, and (5) techniques for evaluating the effectiveness and quality of a data analytics model. Prerequisite: EENG311. 3 hours lecture, 3 semester hours. Prerequisite: EENG311. Co-requisite: None.
**Course Learning Outcomes**

- Describe sources and types of data in modern energy and automation systems.
- Apply MATLAB® commands to analyze data and develop data analytics models.
- Apply stati sti cal analysis tools to process raw data and derive statistical inferences about it.
- Apply regression techniques to model the relationship among continuous variables.
- Divide data points into clusters based on their similarity.
- Use the attributes to data instances in order to assign them to classes.
- Design simple artificial neural networks for various prediction applications.
- Evaluate the performance of a developed data analytics model using appropriate metrics.

- Identify ethical issues related to data analytics models and develop solutions for each one.

**EENG515. MATHEMATICAL METHODS FOR SIGNALS AND SYSTEMS. 3.0 Semester Hrs.**
(I) An introduction to mathematical methods for modern signal processing using vector space methods. Topics include signal representation in Hilbert and Banach spaces; linear operators and the geometry of linear equations; LU, Cholesky, QR, eigen- and singular value decompositions. Applications to signal processing and linear systems are highlighted, such as least-squares estimation, spectral analysis, principal component analysis, and signal classification. Offered every Fall semester.
**Course Learning Outcomes**

- Determine signals and their properties as elements of finite or infinite dimensional vector spaces arising in engineering and science applications.
- Use projection methods to approximate signals when exact representations do not exist.
- Interpret linear operations on signals as linear operators over a vector space and determine range space, null space, norms, adjoints, and inverses.
- Compute optimal solutions to “Ax=y” and key decompositions arising in engineering and science applications.
- Apply eigenspace, principal component analysis, and singular value decompositions of matrix operators to the analysis and design of signals and systems.
- Prove theorems related to signals and systems concepts (Evaluate).
- Design appropriate algorithms for a signal processing and systems application.
- Create presentations of proofs and project work to convince audiences of engineers and scientists of the work’s validity.

**EENG517. THEORY AND DESIGN OF ADVANCED CONTROL SYSTEMS. 3.0 Semester Hrs.**
This course will introduce and study the theory and design of multivariable and nonlinear control systems. Students will learn to design multivariable controllers that are both optimal and robust, using tools such as state space and transfer matrix models, nonlinear analysis, optimal estimator and controller design, and multi-loop controller synthesis. Offered Spring semester of even years. Prerequisite: EENG417.
**Course Learning Outcomes**

- Define control-oriented problem statements for real-world problems.
- Model, analyze, and design controllers and estimators for single-input, single-output (SISO) and multi-input, multi-output (MIMO) systems in time and frequency domains.
- Design optimal and robust controllers and estimators for these systems.
- Model, analyze, and design controllers for nonlinear systems.
- Explain the connection between state-space and transfer function representations of systems and the effects on controller design and analysis.
- Model, analyze, and design feedback control systems using MATLAB and Simulink in both the time and frequency domains.
- Understand and apply basic educational and learning theories and tools that will enhance your lifelong learning.

**EENG519. ESTIMATION THEORY AND KALMAN FILTERING. 3.0 Semester Hrs.**
Estimation theory considers the extraction of useful information from raw sensor measurements in the presence of signal uncertainty. Common applications include navigation, localization and mapping, but applications can be found in all fields where measurements are used. Mathematic descriptions of random signals and the response of linear systems are presented. The discrete-time Kalman Filter is introduced, and conditions for optimality are described. Implementation issues, performance prediction, and filter divergence are discussed. Adaptive estimation and nonlinear estimation are also covered. Contemporary applications will be utilized throughout the course. Offered Spring semester of odd years. 1.5 hours lecture; 1.5 hours other; 3 semester hours.
**Course Learning Outcomes**

- Use Bayes' rule to calculate a statistical inference. Given a description of a stochastic process, calculate the joint and conditional probabilities for this process.
- Using the appropriate algorithm, calculate the probability distribution function for the state of a dynamic system with stochastic inputs.
- Build a model of a dynamic system that includes a probabilistic description of uncertain inputs.
- Design and implement an algorithm to estimate the internal states of a linear system with input signals that are Gaussian stochastic processes.
- Design and implement an algorithm to estimate the internal states of general systems with general stochastic inputs.

**EENG521. NUMERICAL OPTIMIZATION. 3.0 Semester Hrs.**
Optimization is an indispensable tool for many fields of science and engineering. This course focuses on the algorithmic aspects of optimization. Covered topics include first-order (gradient descent and its variants) and second-order methods (Newton and quasi-Newton methods) for unconstrained optimization, theory and algorithms for constrained optimization, stochastic optimization and random search, derivative-free optimization, dynamic programming and simulation-based optimization, and distributed and parallel optimization. The emphasis will be on how the algorithms work, why they work, how to implement them numerically, and when to use which algorithm, as well as applications in different science and engineering fields. Offered Spring semester of odd years.
**Course Learning Outcomes**

- Recognize different types of optimizations, their targeting application areas, and the most suitable algorithms to solve them.
- Understand the mechanisms for different numerical algorithms and the scenarios that they work best.
- Be able to implement optimization algorithms numerically and tune the hyper-parameters.
- Understand optimality conditions for constrained and unconstrained optimizations and use them to design algorithms.
- Use existing optimization packages to quickly prototype and solve optimization formulations of your problems.
- Know how to model, solve, and analyze optimization problems arising in various application fields.

**EENG524. ELECTROMAGNETIC FIELDS AND WAVES. 3.0 Semester Hrs.**
This course provides an introduction to electromagnetic fields and waves and their applications in antennas, radar, high-frequency electronics,

and microwave devices. The time-varying form of electromagnetic fields and the use of sinusoidal time sources to create time-harmonic electromagnetic fields will be covered first, followed by coverage of plane electromagnetic waves formulation and reflection and transmission from different surfaces. Finally, the application of guided electromagnetic waves will be covered through the study of transmission lines, waveguides, and their applications in microwave systems. 3 hours lecture; 3 semester hours. Prerequisite: EENG386.

**Course Learning Outcomes**

- Learn how to work with differential and integral forms of Maxwell's equations and plane electromagnetic waves and use them to design electromagnetic devices
- 2. Learn how to build electromagnetic models and use them to solve electromagnetic problems
- 3. Learn how to develop computer programs to visualize electromagnetic fields such as waveguide modes or signal propagation on transmission lines

**EENG525. ANTENNAS. 3.0 Semester Hrs.**

This course provides an in depth introduction to the analysis and synthesis of antennas and antenna arrays. Students are expected to use MATLAB to model antennas and their performance. An extensive final project that involves experimental or computer demonstrations is required. EENG525 has more depth and required work than EENG425. EENG525 students will have one additional problem for each homework assignment, one additional problem on exam, more difficult paper to review and present, and higher expectations on antenna and direction finding projects. Offered every Spring semester. Prerequisite: EGGN386 or GPGN302 or PHGN384.

**Course Learning Outcomes**

- Develop a good understanding of what approximations are used before designing an antenna.
- Select the proper antenna type according to the required specifications.
- Develop MATLAB programs to aid in the design of antennas and antenna arrays.
- Complete basic analysis and design of an antenna project.
- Design and build a microstrip patch antenna and perform input impedance measurements.
- Design, build, and test an antenna array (for students in EENG525).

**EENG526. ADVANCED ELECTROMAGNETICS. 3.0 Semester Hrs.**

In this course the fundamental theorems of electromagnetics are developed rigorously. Wave solutions are developed in Cartesian, cylindrical, and spherical coordinate systems for bounded and unbounded regions.

**Course Learning Outcomes**

- Develop a good understanding of time harmonic electromagnetic waves.
- Develop a good understanding of electromagnetic theorems and principles.
- Develop and analyze the wave equation solution in different coordinate systems.
- Apply EM boundary conditions to analyze the reflections and transmissions from layered media.
- Develop the formulation and understanding of wave propagation inside waveguides and cavities.
- Develop MATLAB programs to understand the propagation and scattering of electromagnetic waves.

**EENG527. WIRELESS COMMUNICATIONS. 3.0 Semester Hrs.**

Equivalent with EENG513,

This course provides the tools needed to analyze and design a wireless system. Topics include link budgets, satellite communications, cellular communications, handsets, base stations, modulation techniques, RF propagation, coding, and diversity. Students are expected to complete an extensive final project. EENG527 has more depth and required work than EENG427. EENG527 students will have one additional problem for each homework assignment, one additional problem on exam, more difficult paper to review and present, and higher expectations on final project. Offered every Spring semester. Prerequisite: EENG386, EENG311, and EENG388.

**Course Learning Outcomes**

- Calculate the link budget of a wireless communications system.
- Estimate the effects of wireless propagation mechanisms on signals.
- Apply statistical channel models to wireless channels.
- Identify the antenna parameters that are relevant to wireless communications.
- Describe, analyze, and understand the engineering tradeoffs associated with modulation, coding, multiple access, and spread spectrum techniques.
- Write a paper and present a project on an advanced wireless communications topic not covered in class.

**EENG528. COMPUTATIONAL ELECTROMAGNETICS. 3.0 Semester Hrs.**

This course provides the basic formulation and numerical solution for static electric problems based on Laplace, Poisson and wave equations and for full wave electromagnetic problems based on Maxwell's equations. Variation principles methods, including the finite-element method and method of moments will be introduced. Field to circuit conversion will be discussed via the transmission line method. Numerical approximations based on the finite difference and finite difference frequency domain techniques will also be developed for solving practical problems. Offered every Fall semester.

**Course Learning Outcomes**

- Learn how to develop MATLAB programs for electromagnetic problems.
- Learn the different finite difference (FD) mathematical approximations of the derivatives for adaptation to numerical solutions of Maxwell's equations.
- Learn how to convert differential equations into discretized equations and arrange them to form a set of linear equations.
- Learn how to use the finite difference FD for solving electrostatic problems.
- Learn the finite difference frequency domain (FDFD) method and its proper implementations for 1D and 2D electromagnetic problems.
- Learn the finite difference time-domain (FDTD) method and its proper implementations for 2D and 3D electromagnetic problems.
- Learn how to solve antenna problems using the FDTD method.
- Learn how to derive and solve wave propagation through multilayered media.
- Learn how to derive and solve the scattering by circular cylinder.
- Be able to write a good professional project report.

**EENG529. ACTIVE RF & MICROWAVE DEVICES. 3.0 Semester Hrs.**
This course introduces the basics of active radio-frequency (RF) and microwave circuits and devices which are the building blocks of modern communication and radar systems. The topics that will be studied are RF and microwave circuit components, resonant circuits, matching networks, noise in active circuits, switches, RF and microwave transistors and amplifiers. Additionally, mixers, oscillators, transceiver architectures, RF and monolithic microwave integrated circuits (RFICs and MMICs) will be introduced. Moreover, students will learn how to model active devices using professional CAD software, how to fabricate printed active microwave devices, how a vector network analyzer (VNA) operates, and how to measure active RF and microwave devices using VNAs. Offered every Spring semester. Prerequisite: EENG385 and EENG430 or EENG530.
**Course Learning Outcomes**

- Analyze the fundamental system aspects of modern communication and radar systems, comparing and contrasting their key features and functionalities.
- Evaluate the effectiveness of various hardware components used, justifying your selection based on specific design criteria.
- Create designs for active microwave circuits and devices, simulating and optimizing their performance using appropriate modeling techniques.
- Synthesize your knowledge of microwave circuits and devices to develop receiver and transmitter designs.

**EENG530. PASSIVE RF & MICROWAVE DEVICES. 3.0 Semester Hrs.**
This course introduces the basics of passive radio-frequency (RF) and microwave circuits and devices which are the building blocks of modern communication and radar systems. The topics that will be studied are microwave transmission lines and waveguides, microwave network theory, microwave resonators, power dividers, directional couplers, hybrids, RF/microwave filters, and phase shifters. Students will also learn how to design and analyze passive microwave devices using professional CAD software. Moreover, students will learn how to fabricate printed passive microwave devices and test them using a vector network analyzer. Offered every Fall semester.
**Course Learning Outcomes**

- Learn how to analyze transmission line propagation and the effect of discontinuities on the voltages and current distributions.
- Understand transmission line concepts such as reflection coefficient, transmission coefficient, characteristic impedance, impedance, standing-wave ratio, etc.
- Learn how to analyze arbitrary multiport microwave networks using the concepts of S, Z, Y and T parameter matrices.
- Understand the operation principle and analysis of various passive microwave components such as dividers, couplers, resonators and filters.
- Design various passive microwave components considering realistic fabrication constraints with the aid of CAD tools.
- Gain a high level understanding of the operation principle of sub-systems and systems such as radars, transceivers and radiometers, as well as the effects of noise.
- Learn the basics of microwave measurement techniques.

**EENG532. LOW TEMPERATURE MICROWAVE MEASUREMENTS FOR QUANTUM ENGINEERING. 3.0 Semester Hrs.**
The goal of the course is to provide hands on training in high-frequency, low-temperature measurements which are requisite for quantum information applications. This course introduces the fundamentals of high-frequency measurements, the latest techniques for accuracy-enhanced automated microwave measurements, low-temperature measurement techniques, low noise measurements, and common devices used in quantum information. The course will have three modules. The first module, basics of electronic measurements, will include chip layout, power measurements, ground loop testing, impedance measurements, noise fundamentals, cable and device fabrication and care. The second module, high frequency measurements, will include measurements of basic scattering parameters, accuracy enhancement and calibration, transmission line, amplifier, and oscillator characterization including noise measurements. The third module, low-temperature measurements, will cover critical parameters for superconductors and Josephson junctions, measurements of superconducting resonators, characterization of low-temperature electronic elements including amplifiers. At the end of this course the students will know how to use network analyzers, spectrum analyzers, cryostats, the software Eagle for chip design, amplifiers, and filters. Offered every Fall semester.
**Course Learning Outcomes**

- 1. Describe key RF, wireless and microwave measurement parameters
- 2. Understand how to use a range of RF, wireless and microwave test equipment
- 3. Reduce the risk of expensive test equipment damage, repair costs and downtime
- 4. Understand how to correctly perform common RF and microwave measurements
- 5. Understand the basics of low-temperature measurements including critical parameters for superconductors and Josephson junctions, as well as characterization of low-temperature electronic elements
- 6. Better utilize test and measurement equipment features and functionality
- 7. Develop improved problem solving capability due to better understanding

**EENG533. ACTIVE RF & MICROWAVE DEVICES. 3.0 Semester Hrs.**
This course introduces the basics of active radio-frequency (RF) and microwave circuits and devices which are the building blocks of modern communication and radar systems. The topics that will be studied are RF and microwave circuit components, resonant circuits, matching networks, noise in active circuits, switches, RF and microwave transistors and amplifiers. Additionally, mixers, oscillators, transceiver architectures, RF and monolithic microwave integrated circuits (RFICs and MMICs) will be introduced. Moreover, students will learn how to model active devices using professional CAD software, how to fabricate printed active microwave devices, how a vector network analyzer (VNA) operates, and how to measure active RF and microwave devices using VNAs. Offered every Spring semester. Prerequisites: EENG385 and EENG430 or EENG530.
**Course Learning Outcomes**

- Learn how to analyze and design a variety of active RF and microwave devices such as power amplifiers
- Understand the basic operation mechanism of transmitters and receivers in communication systems
- Gain a basic understanding on how vector network analyzers operate and how to measure active microwave devices

- Learn how to model active microwave circuits and devices using a professional CAD tool.

**EENG536. PHASED & ADAPTIVE ARRAYS. 3.0 Semester Hrs.**
This course introduces the basic fundamentals of phased arrays and adaptive antenna arrays with a focus on array processing. The topics that will be introduced are antenna array fundamentals and radiation analysis techniques, elements for antenna arrays, linear, planar, and non-planar arrays, focused arrays, radiation pattern synthesis, phased array and adaptive array system architectures, phase-delay and time-delay systems, analog and digital beamforming, adaptive nulling algorithms and interference cancellation, and angle of arrival estimation algorithms. This foundational knowledge will then be used by the students to conduct a comprehensive course project on a special topic in this area.
**Course Learning Outcomes**

- Learn fundamentals of antenna arrays in linear, planar, and non-planar configurations.
- Learn electronically scanned array operations and characteristics.
- Design, analyze, and characterize the performance of antenna array.
- Learn techniques for array coupling manipulation.
- Develop and design phased array beamforming systems.

**EENG540. INTRODUCTION TO RADAR SYSTEMS. 3.0 Semester Hrs.**
This course provides an introduction to radar system engineering, it covers the fundamental concepts needed to understand the design and operation of modern radar systems for a variety of applications. Topics covered include the radar equation, radar cross section, radar clutter, detection and receiver design, transmitters and antenna systems. Applications include pulsed, continuous-wave, and frequency-modulated radars, Doppler radar, and synthetic aperture radar. Demonstrations will be conducted to complement the theoretical analysis.
**Course Learning Outcomes**

- Understand the basic concepts, operation, and techniques necessary to analyze and access the performance of modern radar systems.
- Learn the components of a radar system and their relationship to overall system performance and to be able to specify the subsystem performance requirements in a radar system design.
- Develop computer programs to analyze and visualize radar signals, phased array patterns, and RSC of targets.

**EENG570. ADVANCED HIGH POWER ELECTRONICS. 3.0 Semester Hrs.**
Basic principles of analysis and design of circuits utilizing high power electronics. AC/DC, DC/AC, AC/AC, and DC/DC conversion techniques. Laboratory project comprising simulation and construction of a power electronics circuit. Offered Fall semester of even years. Prerequisites: EENG470 or instructor consent.
**Course Learning Outcomes**

- Define power electronics and recognize power electronics devices, circuits, and applications.
- Classify converter types and conversion functions, typical of high-voltage and high-power applications.
- Recognize converter topologies, derive their governing equations, and design, analyse and simulate converter circuits.
- Analyze multilevel converters, their operation and control, and comparison with 2-level converters.
- Analyze modular multilevel converters, their design, control, and application.

**EENG572. RENEWABLE ENERGY AND DISTRIBUTED GENERATION. 3.0 Semester Hrs.**
A comprehensive electrical engineering approach on the integration of alternative sources of energy. One of the main objectives of this course is to focus on the inter-disciplinary aspects of integration of the alternative sources of energy which will include most common and also promising types of alternative primary energy: hydropower, wind power, photovoltaic, fuel cells and energy storage with the integration to the electric grid.
**Course Learning Outcomes**

- Understand the fundamentals of renewable energy and distributed energy systems.
- Model renewable and distributed energy systems using EMT and dynamic simulation tools.
- Analyze the integration of renewable and distributed energy systems into power grids.
- Conduct system-level case studies with simulation tools.
- Design and evaluate solutions for the seamless integration of renewable and distributed energy systems into power systems.

**EENG573. ELECTRIC POWER QUALITY. 3.0 Semester Hrs.**
Electric power quality (PQ) deals with problems exhibited by voltage, current and frequency that typically impact end-users (customers) of an electric power system. This course is designed to familiarize the concepts of voltage sags, harmonics, momentary disruptions, and waveform distortions arising from various sources in the system. A theoretical and mathematical basis for various indices, standards, models, analyses techniques, and good design procedures will be presented. Additionally, sources of power quality problems and some remedies for improvement will be discussed. The course bridges topics between power systems and power electronics. Offered Spring semester of even years. Prerequisites:EENG480 and EENG470 or instructor consent.
**Course Learning Outcomes**

- Identify the sources of harmonics and describe how they impact the distribution system
- Propose solutions for mitigating the effects of harmonics in a distribution system
- Determine the root-causes of short-duration voltage variations in distribution grids
- Analyze the causes and effects of long-duration voltage variations in a distribution system
- Propose mitigating solutions for short and long-duration voltage variations
- Identify the sources of transients in distribution systems and propose mitigation techniques
- Simulate various power quality events using engineering software

**EENG577. ADVANCED ELECTRICAL MACHINE DYNAMICS FOR SMART-GRID SYSTEMS. 3.0 Semester Hrs.**
This course provides engineering science analysis and focuses on the application of the abc frame of reference to develop state space and equivalent network models for electric machines and drive systems. The course focuses primarily on the modeling and dynamic performance prediction of electric machines and associated power electronic in smart grids and renewable energy systems/subsystems. The developed

models will be used in computer simulations for the characterization and performance prediction of synchronous and induction machines, permanent magnet synchronous machines synchronous reluctance and switched reluctance machines, as well as other advanced machine systems, such as axil flux generators and Linear PM machines. Offered Spring semester of odd years. Prerequisites: EENG389 and EENG470.

**Course Learning Outcomes**

- Explain power calculations, magnetic fields/circuits/material, and power/torque relationships of energy conversion devices.
- Explain principle of operation of selected energy conversion devices used in smart grid applications.
- Write and explain a device state space model and illustrate, label, and describe a device equivalent circuit model and relate its parameters and terminal inputs/outputs to those of an actual device.
- Use state space models/equivalent circuits to predict and analyze device external operational characteristics (current, voltage, power, energy, torque, speed, losses, efficiency, etc.).
- Compute the energy conversion device model parameters (reactance and resistance) and/or initial conditions (current, voltage, power, torque, speed, losses) and implement utilizing a computer tool (MATLAB/SIMULINK).
- Develop and design a system/sub-system with an energy conversion device. Implement the state space model/equivalent circuit with MATLAB and/or SIMULINK to predict, analyze, and critique the external performance characteristics (current, voltage, power, energy, torque, speed, losses, efficiency, etc.).
- Prepare and write in groups of 2/3 students an IEEE formatted paper to explain, analyze, and critique a case study from one of the modules of weeks 3-7. Present in poster format at the course Final Project: Online Mini-Conference.

**EENG580. POWER DISTRIBUTION SYSTEMS ENGINEERING. 3.0 Semester Hrs.**

This course deals with the theory and applications of problems and solutions as related to electric power distribution systems engineering from both ends: end-users like large industrial plants and electric utility companies. The primary focus of this course in on the medium voltage (4.16 kV ? 69 kV) power systems. Some references will be made to the LV power system. The course includes per-unit methods of calculations; voltage drop and voltage regulation; power factor improvement and shunt compensation; short circuit calculations; theory and fundamentals of symmetrical components; unsymmetrical faults; overhead distribution lines and power cables; basics and fundamentals of distribution protection. Offered in fall semester of odd years. Prerequisites: EENG480 or instructor consent.

**Course Learning Outcomes**

- Comprehend the fundamentals of distribution systems engineering.
- Create and analyze distribution system models.
- Analyze distribution load flow for different scenarios.
- Analyze voltage regulation in distribution systems.
- Comprehend recent advances in distribution automation.
- Apply computational simulation tools to analyze distribution systems.

**EENG581. POWER SYSTEM OPERATION AND MANAGEMENT. 3.0 Semester Hrs.**

This course presents a comprehensive exposition of the theory, methods, and algorithms for Energy Management Systems (EMS) in the power grid. It will focus on (1) modeling of power systems and generation units, (2) methods for dispatching generating resources, (3) methods for accurately estimating the state of the system, (4) methods for assessing the security of the power system, and (5) an overview of the market operations in the grid. Offered Fall semester of even years. Prerequisite: EENG480 or instructor consent.

**Course Learning Outcomes**

- Describe the principles of power generation using renewable and non-renewable energy resources
- Explain root causes of global warming and propose mitigation strategies related to power generation
- Identify ethical issues with energy systems related to the society and the environment
- Design controllers for regulating the voltage and frequency of a synchronous generator
- Apply Newton-Raphson and fast decoupled techniques to solve the power flow problem
- Apply the weighted least squares method to estimate the states of a power system
- Use time-series analysis to forecast the power demand in a distribution system
- Formulate a constrained optimization problem to optimally dispatch generation units in a power grid

**EENG582. HIGH VOLTAGE DC (HVDC) SYSTEMS. 3.0 Semester Hrs.**

This course deals with the theory, modeling and applications of HV and EHV power transmission systems engineering. The primary focus is on overhead AC transmission line and voltage ranges between 115 kV to 500 kV. HVDC and underground transmission will also be discussed. The details include the calculations of line parameters (RLC); steady-state performance evaluation (voltage drop and regulation, losses and efficiency) of short, medium and long lines; reactive power compensation; FACTS devices; insulation coordination; corona; insulators; sag-tension calculations; EMTP, traveling wave and transients; fundamentals of transmission line design; HV and EHV power cables: solid dielectric, oil-filled and gas-filled; Fundamentals of DC transmission systems including converter and filter.

**Course Learning Outcomes**

- Understand HVDC Fundamentals: Learn the core principles, components, and operating mechanisms that di#erentiate HVDC systems from traditional AC systems.
- Explore various HVDC system con#gurations, including back-to-back, point-to-point, and multi-terminal designs, and understand their speci#c applications and technical requirements.
- Design and analyze modular multilevel converter technologies.
- Examine the role of line-commutated and voltage-source converters, their functionalities, and the latest advancements in converter technology.
- Develop knowledge of control methods and protection schemes that ensure the reliable, safe operation of HVDC systems.
- Analyze how HVDC systems facilitate renewable energy integration, long-distance power transfer, and the stability of modern power grids.

**EENG584. POWER SYSTEM RISK MANAGEMENT. 3.0 Semester Hrs.**

This course presents a comprehensive exposition of the theory, methods, and algorithms for risk management in the power grid. The course will focus on: (1) power system stability analysis (steady state, dynamic, and transient), (2) analysis of internal and external threats to power systems, e.g. component failures, faults, natural hazards, cyber intrusions, (3)

introduction to power system security assessment, (4) fundamentals of modeling risk, vulnerability assessment and loss calculations, (5) mitigating techniques before, during and after the course of major events and disturbances. Offered Spring semester of odd years. Prerequisites: EENG480 and EENG481.

**Course Learning Outcomes**

- Identify elements of social vulnerability related to large-scale power outages.
- Define and quantify risk for different engineering applications.
- Assess the stability of a power system in the sense of frequency, rotor angle, and voltage.
- Identify internal or external hazards threatening the stability and security of the power grid.
- Propose solutions for grid resilience before, during and in the aftermath of disturbances.
- Predict the probability and severity of internal or external hazards to power systems.
- Apply MATLAB/Simulink® or PSCAD® to study the dynamics of power systems.

**EENG585. AI FOR POWER AND RENEWABLE ENERGY SYSTEMS. 3.0 Semester Hrs.**

AI is transforming power and energy systems. This course will help students understand and use AI methods and tools and apply them to forecast, analyze, and control power and renewable energy systems. The course starts with an introduction to the mainstream AI tools as well as basic Python programming. Then, the course covers the basics of AI/Machine learning and how to train and test machine learning models. The core of the course will focus on various AI applications in power and renewable energy systems. It provides students many hands-on opportunities to work on real-world-inspired problems. Prerequisite: EENG480.

**Course Learning Outcomes**

**EENG586. COMMUNICATION NETWORKS FOR POWER SYSTEMS. 3.0 Semester Hrs.**

Advanced topics on communication networks for power systems including the fundamentals of communication engineering and signal modulation/transfer, physical layer for data transfer (e.g., wireline, wireless, fiber optics), different communication topologies for power networks (e.g., client-server, peer-to-peer), fundamentals of SCADA system, data modeling and communication services for power system applications, common protocols for utility and substation automation, and cyber-security in power networks. Offered Fall semester of odd years. Prerequisite: EENG480 or instructor consent.

**Course Learning Outcomes**

- List the different layers of the TCP/IP network architecture and explain the role of each one.
- Identify and justify the desired quality-of-service for a given data communication flow between two given components in a power system.
- Choose the appropriate communication media for various telecommunication applications.
- Choose the appropriate parameters for various layers of the TCP/IP network architecture.
- Identify, compare, design, and implement appropriate communication technologies for a given power system.
- Design a communication architecture for a given power system.
- List the common cyber-security threats to a given power system and propose industry-practice countermeasures for each one.

**EENG587. POWER SYSTEMS PROTECTION AND RELAYING. 3.0 Semester Hrs.**

Theory and practice of power system protection and relaying; Study of power system faults and symmetrical components; Fundamental principles and tools for system modeling and analysis pertaining to relaying, and industry practices in the protection of lines, transformers, generators, motors, and industrial power systems; Introduction to microprocessor based relaying, control, and SCADA.

**Course Learning Outcomes**

- Describe the principles and advantages of using symmetrical components for fault analysis.
- Analyze power system unbalanced faults using symmetrical components and convert the results from the sequence domain back to the phase domain.
- Design overcurrent protection for simple feeders using IEEE standard curves and overcurrent protection coordination principles.
- Understand the basic principles of distance protection.
- Model and configure distance protection relays using commercial tool.
- Understand the impact of inverter-based devices on power system fault analysis and protection.

**EENG588. POWER SYSTEM ECONOMICS AND ELECTRICITY MARKETS. 3.0 Semester Hrs.**

This course aims to provide a comprehensive overview of power system economics and electricity market structures and operations. Students will be equipped with essential tools and skills sought by key stakeholders in the electric power sector, enabling them to properly formulate and solve optimization problems in power system economics, calculate and evaluate locational marginal prices, and analyze different market frameworks and ancillary services while considering future opportunities and challenges. The course content aligns with major energy industry trends, such as decarbonization, digitalization, and decentralization, preparing students to drive advancements in power system efficiency, affordability, and sustainability. In doing so, it supports engineers in advancing their careers in the energy sector and contributes meaningfully to the power industry's transformation. Prerequisites: EENG480 or instructor consent.

**Course Learning Outcomes**

- Distinguish different electricity market frameworks (i.e., market structures, trading mechanisms, and regulatory mechanisms) at both wholesale and retail level.
- Formulate market clearing, economic dispatch, and unit commitment problems using deterministic and stochastic mathematical optimization models.
- Determine locational marginal prices considering generation and transmission constraints.
- Solve convex optimization problems in power system economics using computational tools.
- Distinguish different types of ancillary services and their procurement processes in different jurisdictions.
- Assess the impact of extreme events on wholesale electricity prices using real-world data.

- Analyze opportunities, challenges, and needs in existing electricity markets to support increased decarbonization, digitalization, and decentralization in the power sector.

**EENG589. DESIGN AND CONTROL OF WIND ENERGY SYSTEMS. 3.0 Semester Hrs.**
Wind energy provides a clean, renewable source for electricity generation. Wind turbines provide electricity at or near the cost of traditional fossil-fuel fired power plants at suitable locations, and the wind industry is growing rapidly as a result. Engineering R&D can still help to reduce the cost of energy from wind, improve the reliability of wind turbines and wind farms, and help to improve acceptance of wind energy in the public and political arenas. This course will provide an overview of the design and control of wind energy systems. Offered Spring semester of odd years. Prerequisite: EENG307.
**Course Learning Outcomes**

- Evaluate the benefits and drawbacks of wind energy and its role in a sustainable energy future.
- Organize wind energy systems around their major subsystems, including but not limited to the wind resource, rotor aerodynamics, turbine mechanical dynamics, electrical systems of the turbine and utility interconnection, control system, and broader contexts in which these systems are located.
- Design a controller for a wind energy system under time-varying wind input conditions, model this controller using available software, and evaluate its benefits and drawbacks.
- Develop and then conduct a research project for specific wind energy application.
- Improve your student- and self-driven learning skills.

**EENG597. SUMMER PROGRAMS. 0-6 Semester Hr.**

**EENG598. SPECIAL TOPICS IN ELECTRICAL ENGINEERING. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**EENG598. SPECIAL TOPICS. 0-6 Semester Hr.**

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**EENG598. SPECIAL TOPICS IN ELECTRICAL ENGINEERING. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**EENG599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**EENG599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

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**EENG600. GRADUATE SEMINAR ON SMART-GRID ELECTRICAL POWER AND ENERGY SYSTEMS. 3.0 Semester Hrs.**
(I, II, S) In this course, learners will plan, develop, and present a research project in their field of technology on a subject related to Smart-Grid, Electrical Power, and Energy Systems. Their chosen topic and seminar must demonstrate their knowledge and skills in scientific and engineering analysis and modeling, project handling, technical writing, problem-solving, evaluation and assessment of their goals, and oral presentation techniques. Learners will advance their research training in the design of future electric power grids, conduct analysis, simulation and data evaluation of electricity infrastructure in the area of Smart Cities, prosumers and distributed generation and will attend and make seminar or another modern presentation on cutting-edge issues of enhanced livability, enhanced workability, and increased sustainability for Transportation and Electrification, Power System Resiliency, Energy Economy, Community Micro-grids, Data Analytics, and Renewable Energy. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Advance their research training in the design of future electric power grids with high penetration of renewable energy and electrical energy storage
- Conduct analysis, simulation and data evaluation of electricity infrastructure in the area of Smart Cities, prosumers and distributed generation
- Prepare and make a seminar presentation in a very dynamic and modern format on cutting edge issues of enhanced livability, enhanced workability, and enhanced sustainability for Transportation and Electrification, Power System Resiliency, Energy Economy, Community, Micro-grids, Data Analytics, and Renewable Energy
- Communicate (in oral and written formats) results to a both a technical as well as a non-technical audience

**EENG617. INTELLIGENT CONTROL SYSTEMS. 3.0 Semester Hrs.**
Fundamental issues related to the design on intelligent control systems are described. Neural networks analysis for engi neering systems are presented. Neural-based learning, estimation, and identification of dynamical systems are described. Qualitative control system analysis using fuzzy logic is presented. Fuzzy mathematics design of rule-based control, and integrated human-machine intelligent control systems are covered. Real-life problems from different engineering systems are analyzed. Prerequisite: EENG517. 3 hours lecture; 3 semester hours. Taught on demand.

**EENG618. NONLINEAR AND ADAPTIVE CONTROL. 3.0 Semester Hrs.**
This course presents a comprehensive exposition of the theory of nonlinear dynamical systems and the applications of this theory to adaptive control. It will focus on (1) methods of characterizing and understanding the behavior of systems that can be described by nonlinear ordinary differential equations, (2) methods for designing controllers for such systems, (3) an introduction to the topic of system identification, and (4) study of the primary techniques in adaptive control, including model-reference adaptive control and model predictive control. Offered on demand. Prerequisite: EENG517.

**EENG683. COMPUTER METHODS IN ELECTRIC POWER SYSTEMS. 3.0 Semester Hrs.**
This course deals with the computer methods and numerical solution techniques applied to large scale power systems. Primary focus includes load flow, short circuit, voltage stability and transient stability studies and contingency analysis. The details include the modeling of various devices like transformer, transmission lines, FACTS devices, and synchronous machines. Numerical techniques include solving a large set of linear or non-linear algebraic equations, and solving a large set of differential equations. A number of simple case studies (as per IEEE standard models) will be performed. Prerequisites: EENG580 and EENG582 or equivalent; a strong knowledge of digital simulation techniques. 3 lecture hours; 3 semester hours. Taught on demand.

**EENG698. SPECIAL TOPICS IN ELECTRICAL ENGINEERING. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**EENG699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**EENG707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.**
(I, II, S) Research credit hours required for completion of a Masters-level thesis or Doctoral dissertation. Research must be carried out under the direct supervision of the student's faculty advisor. Variable class and semester hours. Repeatable for credit.

## Professor and Department Head

Peter Aaen

## Professors

Atef Elsherbeni

Kathryn Johnson

Tyrone Vincent

Michael Wakin

## Associate Professors

Qiuhua Huang

Salman Mohagheghi

## Assistant professors

Omid Beik

Yamuna Phal

Gabriel Santamaria-Botello

## Teaching Professors

Abd Arkadan

Chris Coulston

## Teaching Associate Professor

Prachi Sharma

## Teaching Assistant Professor

Hisham Sager

## Emeriti Professor

Ravel Ammerman, Emeritus Teaching Professor

Pankaj (PK) Sen, Emeritus Professor

Jeffrey Schowalter, Emeritus Teaching Professor

Marcelo Simoes, Emeritus Professor

Catherine Skokan, Emerita Associate Professor

# Geology and Geological Engineering

## Degrees Offered

- Master of Science (Geology)
- Master of Science (Geological Engineering)
- Doctor of Philosophy (Geology)
- Doctor of Philosophy (Geological Engineering)
- Master of Engineering (Geological Engineering) (non-thesis)
- Professional Master's Degree (Mineral Exploration) (non-thesis)
- Graduate Certificate of Economic Geology
- Graduate Certificate of Exploration Methods

## Program Description

The Department of Geology and Geological Engineering offers Master of Science and Doctor of Philosophy degrees in Geology; and Master of Engineering, and Master of Science and Doctor of Philosophy degrees in Geological Engineering. Professional Master Degrees are offered in Mineral Exploration. Geological Engineering degrees require possession or acquisition of an undergraduate engineering degree or its equivalent.

Graduate students desiring to study ground water, engineering geology/geotechnics, mining engineering geology and some environmental applications are generally expected to pursue the Geological Engineering degree. Students desiring to study petroleum or minerals exploration

or development sciences, and/or geology generally pursue geology degrees.

Geoscience students may also choose among several interdisciplinary graduate programs comprised of faculty from several different Mines departments. The most common choices are Geochemistry, Hydrologic Science and Engineering, and Underground Construction and Tunnel Engineering. Please see sections in the catalog for each of these programs.

## Program Details for Geology Degrees

**The Master of Science (Geology)** program will require 36 credits of course and research credits. Twelve of the 36 credits must be research credits. All master of science (Geology) candidates must also complete an appropriate thesis based upon original research they have conducted. A thesis proposal and course of study must be approved by the student's thesis advisory committee before the candidate begins substantial work on the thesis research.

**The Doctor of Philosophy (Geology)** academic program requires a minimum of 72 hours of course and research credits. At least 24 of the hours must be research credits and at least 36 must be course credits. Students who enter the PhD program with a thesis-based master's degree may transfer up to 36 credits in recognition of the coursework and research completed for that degree (up to 24 of these credits can come from previous graduate-level coursework). The specific courses and total number of hours that may transfer are at the discretion of the student's doctoral thesis advisory committee. All PhD (Geology) students must pass a comprehensive examination, which is expected to be conducted immediately following the semester in which the required 36 course credits have been completed, and no later than by the end of the second year of their program. This timing may be adjusted for part-time students. This examination will be administered by the student's doctoral committee and will consist of an oral and a written examination, administered in a format to be determined by the doctoral Committee. Two negative votes in the doctoral Committee constitute failure of the examination. Depending on the outcome of the qualifying examination, the doctoral thesis advisory committee can recommend students to take up to 6 additional course credits. In case of failure of the qualifying examination, a re-examination may be given upon the recommendation of the doctoral committee and approval of the graduate dean. Only one re-examination may be given. Students must also complete an appropriate thesis based upon original research they have conducted and are encouraged to have submitted at least two manuscripts based on the dissertation work for publication in peer-reviewed scholarly journals before defending their thesis. A thesis proposal and course of study must be approved by the student's doctoral thesis advisory committee before the student begins substantial work on the thesis research.

**Core Competencies for Geology Degrees**

No specific prerequisites are required for admission to the Geology degree program. However, the following courses are identified as Core Competencies that are highly recommended for completion prior to application to the Geology Graduate Program:

- General Geology
- Field methods/ field camp
- Structural Geology
- Mineralogy
- Petrology
- Sedimentology/ Stratigraphy
- Chemistry (three semesters, including at least one semester of physical or organic)
- Mathematics (two semesters of calculus)
- An additional science course (other than geology) or advanced mathematics
- Physics (two semesters)

Generally speaking, if not satisfied through previous bachelor's-level coursework, the Core Competency requirements should be completed during the course of the **Master of Science (Geology) or Doctor of Philosophy (Geology)** program. Specific Core Competency requirements may be waived by the student's thesis committee.

## Program Details for Geological Engineering Degrees

**The Master of Science (Geological Engineering)** program requires 36 credits of course and research credits. 12 of the 36 credits must be research credits, and 24 of the credits must be earned through the completion of coursework. All Master of Science (Geological Engineering) candidates must also complete an appropriate thesis, based upon original research they have conducted. A thesis proposal and course of study must be approved by the student's Thesis Advisory Committee before the candidate begins substantial work on the thesis research.

**The Doctor of Philosophy (Geological Engineering)** academic program requires a minimum of 72 hours of course and research credits. At least 24 of the hours must be research credits, and at least 24 of the hours must be earned through completion of coursework. Students who enter the PhD program with a thesis-based master's degree may transfer up to 36 credits in recognition of the coursework and research completed for that degree (up to 24 of these credits can come from previous graduate-level coursework). The specific courses and total number of hours that may transfer are at the discretion of the student's doctoral thesis advisory committee.

All Doctor of Philosophy (Geological Engineering) students must pass a comprehensive examination by the end of the second year of their program. This timing may be adjusted for part-time students. This examination will be administered by the student's doctoral committee and will consist of an oral and a written examination, administered in a format to be determined by the doctoral committee. Two negative votes in the doctoral committee constitute failure of the examination. In case of failure of the qualifying examination, a re-examination may be given upon the recommendation of the doctoral committee and approval of the graduate dean. Only one re-examination may be given. Students must also complete appropriate thesis based upon original research they have conducted. A thesis proposal and course of study must be approved by the student's doctoral thesis advisory committee before the student begins substantial work on the thesis research.

**Core Competencies for Geological Engineering Degrees**
The candidate for the degree of **Master of Science (Geological Engineering) or Doctor of Philosophy (Geological Engineering)** must have completed the following or equivalent subjects prior to graduation. These may be satisfied through previous bachelor's-level coursework or during the graduate program. Credit will only be granted for graduate-level courses that are equivalent to the titles below.

**Mathematics**

- Calculus (two semesters)
- One semester in two of the following subjects:
  - Calculus III
  - Differential Equations
  - Probability and Statistics
  - Numerical Analysis
  - Linear Algebra
  - Operations Research
  - Optimization

**Basic Science**

- Chemistry (2 semesters)
- Mineralogy and Petrology
- Physics (2 semesters)
- Stratigraphy or Sedimentation
- Physical Geology
- Computer Programming or GIS

**Engineering Science**

- Structural Geology
- Soil Mechanics
- Rock Mechanics
- One semester in two of the following subjects:
  - Physical Chemistry or Thermodynamics
  - Statics
  - Mechanics of Materials
  - Fluid Mechanics
  - Dynamics

**Engineering Design**

- Field Geology
- Engineering Geology
- Hydrogeology
- One semester in three of the following subjects:
  - Foundation Engineering
  - Engineering Hydrology
  - Geomorphology
  - Remote Sensing or GIS
  - Introductory Geophysics
  - Engineering Geology Design
  - Groundwater Engineering Design
  - Other engineering design courses as approved by the program committee

## Program Requirements for Geological Engineering Degrees

In addition to the core competency requirements, the **Master of Science or Doctor of Philosophy degrees with specialization in Engineering Geology/Geotechnics** require:

| | | |
|---|---|---|
| GEGN532 | GEOLOGICAL DATA ANALYSIS | 3.0 |
| Candidates must also take at least three of the following: | | |
| GEGN563 | APPLIED NUMERICAL MODELLING FOR GEOMECHANICS | 3.0 |
| GEGN570 | CASE HISTORIES IN GEOLOGICAL ENGINEERING AND HYDROGEOLOGY | 3.0 |
| or GEGN673 | ADVANCED GEOLOGICAL ENGINEERING DESIGN | |
| GEGN573 | GEOLOGICAL ENGINEERING SITE INVESTIGATION | 3.0 |
| GEGN575 | APPLICATIONS OF GEOGRAPHIC INFORMATION SYSTEMS | 3.0 |
| or GEGN580 | APPLIED REMOTE SENSING FOR GEOENGINEERING AND GEOSCIENCES | |
| or GEGN568 | POINT CLOUD DATA ANALYSIS IN EARTH SCIENCE AND ENGINEERING | |
| GEGN671 | LANDSLIDES: INVESTIGATION, ANALYSIS & MITIGATION | 3.0 |

Typically, the additional courses are selected from the following topical areas: engineering geology, groundwater engineering, groundwater modeling, soil mechanics and foundations, rock mechanics, underground construction, seismic hazards, geomorphology, geographic information systems, construction management, finite element modeling, waste management, environmental engineering, environmental law, engineering management, and computer programming.

## Program Details for Non-Thesis Master of Engineering Degrees

**The Master of Engineering (non-thesis) Program in Geological Engineering** outlined below may be completed by individuals already holding undergraduate or advanced degrees or as a **combined undergraduate/graduate degree program** by individuals already matriculated as undergraduate students at Colorado School of Mines. The program is comprised of 24 hours of coursework and 6 hours of independent study (non-thesis project) for a total of 30 credits. The Master of Engineering (Non-Thesis) Program in Geological Engineering has the same Core Competency requirements as the Geological Engineering Master of Science and Doctor of Philosophy degrees.

## Mines' Combined Undergraduate/Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

The typical program plan includes 12 course credits in both the fall and the spring terms followed by 6 independent study credits during the summer term.

GEGN599 requires a project and report that demonstrate competence in the application of geological engineering principles that merits a grade of B or better. The project topic and content of the report is determined by

the student's advisor, in consultation with the student. The format of the report will follow the guidelines for a professional journal paper.

In consultation with the advisor, the student must prepare a formal program of courses and independent study topic for approval by the Geological Engineering Graduate Program Committee. The program must be submitted to the committee on or before the end of the first week of classes of the first semester.

The **Master of Engineering (non-thesis)** requires the following courses in addition to the Core Competencies:

| | | |
|---|---|---|
| GEGN532 | GEOLOGICAL DATA ANALYSIS | 3.0 |
| GEGN599 | INDEPENDENT STUDY | 6.0 |
| Candidates must also take at least three of the following: | | |
| GEGN563 | APPLIED NUMERICAL MODELLING FOR GEOMECHANICS | 3.0 |
| GEGN570 | CASE HISTORIES IN GEOLOGICAL ENGINEERING AND HYDROGEOLOGY | 3.0 |
| or GEGN673 | ADVANCED GEOLOGICAL ENGINEERING DESIGN | |
| GEGN573 | GEOLOGICAL ENGINEERING SITE INVESTIGATION | 3.0 |
| GEGN575 | APPLICATIONS OF GEOGRAPHIC INFORMATION SYSTEMS | 3.0 |
| or GEGN580 | APPLIED REMOTE SENSING FOR GEOENGINEERING AND GEOSCIENCES | |
| or GEGN568 | POINT CLOUD DATA ANALYSIS IN EARTH SCIENCE AND ENGINEERING | |
| GEGN671 | LANDSLIDES: INVESTIGATION, ANALYSIS & MITIGATION | 3.0 |

Electives and course substitutions are approved by the advisor. Possibilities for other electives include graduate- level rock mechanics and rock engineering, soil mechanics and foundations, groundwater, site characterization, geographical information systems (GIS), project management and geophysics, for example.

## Program Details for Graduate Certificates

## Certificate and Degree Requirements

We offer two graduate certificates and a professional master's degree (non-thesis). The courses taken for certificate degrees can be used toward the professional master's degree.

The Graduate Certificate Programs in Economic Geology and Exploration Methods outlined below may be completed by individuals already holding undergraduate or advanced degree in geology or a related field and have at least two to three years of professional experience. The programs are comprised of:

| | |
|---|---|
| Course Work | 12.0 Credits |
| Total Semester Hrs | 12.0 Credits |

**Graduate Certificate of Economic Geology**

Students working toward a Graduate Certificate of Economic Geology are required to take at least 6 credits out of the following courses; courses cannot be used in fulfilling the requirements of other certificates:

**Core courses:**

| | | |
|---|---|---|
| GEOL513 | HYDROTHERMAL GEOCHEMISTRY | 3.0 |
| GEOL521 | FIELD AND ORE DEPOSIT GEOLOGY | 3.0 |
| GEOL524 | ORE DEPOSIT MODELS AND EXPLORATION STRATEGIES | 3.0 |

Students working toward a Graduate Certificate of Economic Geology can choose up to 6 credits out of the following courses' courses cannot be used in fulfilling the requirements of other certificates:

**Electives:**

| | | |
|---|---|---|
| GEOL505 | ADVANCED STRUCTURAL GEOLOGY | 3.0 |
| GEOL520 | NEW DEVELOPMENTS IN THE GEOLOGY AND EXPLORATION OF ORE DEPOSITS | 2.0 |
| GEOL523 | REFLECTED LIGHT AND ELECTRON MICROSCOPY | 2.0 |
| GEOL628 | ADVANCED IGNEOUS PETROLOGY | 3.0 |
| GEOL645 | VOLCANOLOGY | 3.0 |
| CHGC503 | INTRODUCTION TO GEOCHEMISTRY | 3.0 |

## Graduate Certificate of Exploration Methods

Students working toward a Graduate Certificate of Economic Geology are required to take at least 6 credits out of the following courses; courses cannot be used in fulfilling the requirements of other certificates:

**Core courses:**

| | | |
|---|---|---|
| GEGX571 | GEOCHEMICAL EXPLORATION | 3.0 |
| GEOL520 | NEW DEVELOPMENTS IN THE GEOLOGY AND EXPLORATION OF ORE DEPOSITS | 2.0 |
| GEOL523 | REFLECTED LIGHT AND ELECTRON MICROSCOPY | 2.0 |
| GPGN598 | GEOPHYSICS FOR MINERAL EXPLORATION | 3.0 |

Students working toward a Graduate Certificate of Economic Geology can choose up to 6 credits out of the following courses; courses cannot be used in fulfilling the requirements of other certificates:

**Electives:**

| | | |
|---|---|---|
| GEGN501 | MINERAL DEPOSITS | |
| GEGN502 | MINERAL EXPLORATION DESIGN | |
| GEGN532 | GEOLOGICAL DATA ANALYSIS | 3.0 |
| GEGN575 | APPLICATIONS OF GEOGRAPHIC INFORMATION SYSTEMS | 3.0 |
| GEGN588 | ADVANCED PLANETARY GEOGRAPHIC INFORMATION SYSTEMS | 3.0 |
| GEOL501 | APPLIED STRATIGRAPHY | 4.0 |
| GEOL514 | BUSINESS OF ECONOMIC GEOLOGY | 3.0 |
| GEOL521 | FIELD AND ORE DEPOSIT GEOLOGY | 3.0 |
| GEOL524 | ORE DEPOSIT MODELS AND EXPLORATION STRATEGIES | 3.0 |
| GEOL526 | PLATE TECTONICS | 3.0 |
| GEOL555 | STRUCTURAL FIELD RESEARCH | 4.0 |
| GEOL598 | SEMINAR IN GEOLOGY OR GEOLOGICAL ENGINEERING (Skarns and Related Deposits) | 3.0 |
| GEOL601 | CORE TO OUTCROP STRATIGRAPHY | 2.0 |

| | | |
|---|---|---|
| MNGN510 | FUNDAMENTALS OF MINING AND MINERAL RESOURCE DEVELOPMENT | 3.0 |
| MNGN528 | MINING GEOLOGY | 3.0 |
| CHGC504 | METHODS IN GEOCHEMISTRY | 3.0 |

## Mines Combined Undergraduate/Graduate Program

Students enrolled in Mines combined undergraduate/graduate program may double count up to  credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

# Program Details for Professional Master Degrees

Candidates for the Professional Master Degree must possess an appropriate geosciences undergraduate degree or its equivalent. Prerequisites are the same as those required for the Master of Science (Geology) Degree.

## Professional Master in Mineral Exploration

This non-thesis, master's degree program is designed for working professionals who want to increase their knowledge and skills, while gaining a thorough update of advances across the spectrum of economic geology, mineral exploration techniques, and mining geosciences. Admission to the program is competitive. Preference will be given to applicants with a minimum of two years of industrial or equivalent experience.

The program requires a minimum of 30 credits of coursework, and no research is required. A minimum of 15 credits must be accumulated in five of the following core areas:

- Mineral Deposits,
- Mineral Exploration,
- Applied Geophysics,
- Applied Geochemistry,
- Applied Structural Geology,
- Petrology,
- Field Geology,
- Economic Evaluation.

An additional 15 credits may be selected from the course offerings of the Department of Geology and Geological Engineering and allied departments including Mining Engineering, Economics and Business, Geophysics, Chemistry and Geochemistry, Metallurgy and Materials Science, and Environmental Sciences.

Selection of courses will be undertaken in consultation with the academic advisor. A maximum of 9 credits may be independent study focusing on a topic relevant to the mineral exploration and mining industries.

## Mines Combined Undergraduate/Graduate Program

Students enrolled in Mines combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

# Courses

**GEGN501. MINERAL DEPOSITS. 4.0 Semester Hrs.**
Introductory presentation of magmatic, hydrothermal, and sedimentary metallic ore deposits. Chemical, petrologic, structural, and sedimentological processes that contribute to ore formation. Description of classic deposits representing individual deposit types. Review of exploration sequences. Laboratory consists of hand specimen study of host rock-ore mineral suites and mineral deposit evaluation problems. Prerequisite: GEGN307, GEGN316.
**Course Learning Outcomes**

- Understand what economic geologists do (exploration and mining geologists).
- Understand the interface between geology and mining engineering, metallurgy, and environmental science).
- Understand the basic types of metallic mineral deposits through lectures, readings, and laboratory examination of samples.
- Enhance student’s reading and writing skills.
- Enhance student’s ability to solve mineral exploration problems utilizing geologic maps and cross sections.

**GEGN502. MINERAL EXPLORATION DESIGN. 3.0 Semester Hrs.**
Exploration project design: commodity selection, target selection, genetic models, alternative exploration approaches and associated costs, exploration models, property acquisition, and preliminary economic evaluation. Lectures and laboratory exercises to simulate the entire exploration sequence from inception and planning through implementation to discovery, with initial ore reserve calculations and preliminary economic evaluation. Prerequisite: GEGN501, GEGN475 (or concurrent enrollment).
**Course Learning Outcomes**

- Same

**GEGN503. INTEGRATED EXPLORATION AND DEVELOPMENT. 3.0 Semester Hrs.**
(I) Students work alone and in teams to study reservoirs from fluvial-deltaic and valley fill depositional environments. This is a multidisciplinary course that shows students how to characterize and model subsurface reservoir performance by integrating data, methods and concepts from geology, geophysics and petroleum engineering. Activities include field trips, computer modeling, written exercises and oral team presentations. Prerequisite: none. 2 hours lecture, 3 hours lab; 3 semester hours. Offered fall semester, odd years.
**Course Learning Outcomes**

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**GEGN504. INTEGRATED EXPLORATION AND DEVELOPMENT. 3.0 Semester Hrs.**
(I) Students work in multidisciplinary teams to study practical problems and case studies in integrated subsurface exploration and development. The course addresses emerging technologies and timely topics with a general focus on carbonate reservoirs. Activities include field trips, 3D computer modeling, written exercises and oral team presentation. Prerequisite: none. 3 hours lecture and seminar; 3 semester hours. Offered fall semester, even years.
**Course Learning Outcomes**

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**GEGN508. ADVANCED ROCK MECHANICS. 3.0 Semester Hrs.**
Equivalent with MNGN418, Analytical and numerical modeling analysis of stresses and displacements induced around engineering excavations in rock. Insitu stress. Rock failure criteria. Complete load deformation behavior of rocks. Measurement and monitoring techniques in rock mechanics. Principles of design of excavation in rocks. Analytical, numerical modeling and empirical design methods. Probabilistic and deterministic approaches to rock engineering designs. Excavation design examples for shafts, tunnels, large chambers and mine pillars. Seismic loading of structures in rock. Phenomenon of rock burst and its alleviation. Prerequisite: MNGN321.
**Course Learning Outcomes**

- Identical to MNGN508 ADVANCED ROCK MECHANICS course

**GEGN509. INTRODUCTION TO AQUEOUS GEOCHEMISTRY. 3.0 Semester Hrs.**
(I) Analytical, graphical and interpretive methods applied to aqueous systems. Thermodynamic properties of water and aqueous solutions. Calculations and graphical expression of acid-base, redox and solution-mineral equilibria. Effect of temperature and kinetics on natural aqueous systems. Adsorption and ion exchange equilibria between clays and oxide phases. Behavior of trace elements and complexation in aqueous systems. Application of organic geochemistry to natural aqueous systems. Light stable and unstable isotopic studies applied to aqueous systems. Prerequisite: DCGN209 or equivalent. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

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**GEGN520. INDUSTRIAL MINERALS AND ROCKS. 3.0 Semester Hrs.**
Introduction to the Industrial Minerals industry via appreciation of geologic occurrence, physical and chemical material properties, mining and processing considerations, and marketing of various commodities. Development of skills in preparation of commodity surveys, reserves and resources classifications, and project appraisals. Required field trips to operational sites and trip reports. Mid-term and final exams. Individual student commodity term project and presentation. Prerequisite: Senior or graduate status in earth resources field. 3 hours lecture/seminar; 3 semester hours. Offered alternate years when student demand is sufficient.
**Course Learning Outcomes**

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**GEGN527. ORGANIC GEOCHEMISTRY OF FOSSIL FUELS AND ORE DEPOSITS. 3.0 Semester Hrs.**
(II) A study of organic carbonaceous materials in relation to the genesis and modification of fossil fuel and ore deposits. The biological origin of the organic matter will be discussed with emphasis on contributions of microorganisms to the nature of these deposits. Biochemical and thermal changes which convert the organic compounds into petroleum, oil shale, tar sand, coal, and other carbonaceous matter will be studied. Principal analytical techniques used for the characterization of organic matter in the geosphere and for evaluation of oil and gas source potential will be discussed. Laboratory exercises will emphasize source rock evaluation, and oil-source rock and oil-oil correlation methods. Prerequisite: CHGN221, GEGN438. 2 hours lecture; 3 hours lab; 3 semester hours. Offered alternate years.
**Course Learning Outcomes**

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**GEGN530. CLAY CHARACTERIZATION. 2.0 Semester Hrs.**
Equivalent with GEOL530,
(I) Clay mineral structure, chemistry and classification, physical properties (flocculation and swelling, cation exchange capacity, surface area and charge), geological occurrence, controls on their stabilities. Principles of X-ray diffraction, including sample preparation techniques, data collection and interpretation, and clay separation and treatment methods. The use of scanning electron microscopy to investigate clay distribution and morphology. Methods of measuring cation exchange capacity and surface area. Prerequisites: GEGN206. 1 hour lecture, 3 hours lab; 2 semester hours.
**Course Learning Outcomes**

- No change

**GEGN532. GEOLOGICAL DATA ANALYSIS. 3.0 Semester Hrs.**
(II) Techniques and strategy of data analysis in geology and geological engineering: basic statistics review, mapping, sampling and sample representativity, univariate and multivariate statistics, regression, hypothesis testing, cluster and discriminant analysis, principal component analysis, geostatistics. Practical experience in learning to write code in Matlab and use of data sets from case histories. 3 hours lecture; 3 semester hours. Prerequisite: MATH201 or MATH530 and MATH 332 or equivalent.
**Course Learning Outcomes**

- 1) Demonstration of exemplary disciplinary expertise. 2) Demonstration of a set of professional skills necessary to succeed in a student's chosen career path.

**GEGN542. ADVANCED DIGITAL TERRAIN ANALYSIS. 3.0 Semester Hrs.**
Application of GIS and Remote Sensing principles to solve geoscience and geological engineering problems, with an emphasis on modeling and visualizing the surface of the Earth, performing analysis and support decision making for a variety of applications. Course will present in-depth analysis of specific digital terrain analysis techniques, followed by application exercises. Topics will include analysis and hazard studies of erosion, landslides, stream restoration, wildfire, and environmental issues.
**Course Learning Outcomes**

- Identification dominant geologic processes operating on an area and estimate the process rate, maturity of the resulting landscape, and the associated hazards and other impacts to infrastructure and natural resources
- Selection and application of analytical tools to interpret geomorphological data to provide quantitative assessment of

processes, predict future landscape response, and assess hazard and risk
- Use GIS tools and remote sensing data to analyze landscape features and quantify hazards.

**GEGN561. UNDERGROUND CONSTRUCTION ENGINEERING LABORATORY. 1.0 Semester Hr.**
This course provides students with hands-on experience with tools and skills which are commonly used in the underground construction industry. Weekly labs integrate with other courses in the field of Underground Construction and Tunnel Engineering. Pre-requisites: Graduate standing in Underground Construction and Tunnel Engineering, Civil engineering, Mining engineering, or Geological Engineering.
**Course Learning Outcomes**

- Reinforce concepts learned in lecture courses
- Provide students with hands-on experience with common tools in the UC industry

**GEGN563. APPLIED NUMERICAL MODELLING FOR GEOMECHANICS. 3.0 Semester Hrs.**
(I) Course focuses on a comprehensive suite of numerical analysis techniques suited to geotechnical design with a focus on excavations in rock/soil and landslides. Finite element, finite difference, discrete/distinct element and boundary element methods are all discussed with hands-on application workshops using state-of-the-art geomechanics software. Analytical models and pre- and post- processing techniques suited to typical rock engineering problems are developed through assignments. Strength criteria and non-linear inelastic constitutive models for continuum plasticity, brittle fracture and discontinuum deformation are explored in detail. Projects involving real case histories are undertaken to highlight the application of and engineering judgment associated with numerical analysis for problems involving rockmasses. Prerequisites: GEGN468, MNGN321 or CEEN312. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Understand the fundamentals of various computation techniques
- Utilize numerical modelling software to solve geomechanics design problems
- Think critically about the practical strengths and limitations of different modelling approaches

**GEGN566. GROUNDWATER ENGINEERING. 3.0 Semester Hrs.**
(I) Theory of groundwater occurrence and flow. Relation of groundwater to surface water; hydraulic head distribution and flow; theory of aquifer tests; water chemistry, water quality, and contaminant transport. 3 hours lecture, 3 semester hours. Prerequisite: Calc III (MATH213 or MATH223) and DiffEQ (MATH225 or MATH235) and GEGN351 or MEGN351.
**Course Learning Outcomes**

- No changes to current class outcomes.

**GEGN568. POINT CLOUD DATA ANALYSIS IN EARTH SCIENCE AND ENGINEERING. 3.0 Semester Hrs.**
This course is intended to expose students to the fundamentals of point cloud data collection, processing and analysis. In-class exercises, homework assignments and readings will expose students to a broad array of earth science and geological engineering applications and provide hands-on experience with current academic/government/industry standard software. In consultation with the instructors, each student will design and implement a unique term project using point cloud data to advance their own research interests and goals.

**Course Learning Outcomes**

- 1)
- 2)
- 3)
- 4)

**GEGN570. CASE HISTORIES IN GEOLOGICAL ENGINEERING AND HYDROGEOLOGY. 3.0 Semester Hrs.**
(I) Case histories in geological and geotechnical engineering, ground water, and waste management problems. Students are assigned problems and must recommend solutions and/or prepare defendable work plans. Discussions center on the role of the geological engineer in working with government regulators, private-sector clients, other consultants, and other special interest groups. Prerequisite: GEGN467, GEGN468, GEGN469, GEGN470. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

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**GEGN571. ADVANCED ENGINEERING GEOLOGY. 3.0 Semester Hrs.**
Emphasis will be on engineering geology mapping methods, and geologic hazards assessment applied to site selection and site assessment for a variety of human activities. Prerequisite: GEGN468 or equivalent. 2 hours lecture, 3 hours lab; 3 semester hours. Offered alternate years.
**Course Learning Outcomes**

- .

**GEGN572. ENGINEERING GEOLOGY AND GEOTECHNICS. 4.0 Semester Hrs.**
(I) Application of geology to evaluation of construction, mining, and environmental projects such as dams, water ways, tunnels, highways, bridges, buildings, mine design, and land-based waste disposal facilities. Design projects including field, laboratory, and computer analysis are an important part of the course. 3 hours lecture, 3 hours lab, 4 semester hours. Prerequisite: MNGN321, CEEN312, CEEN312L.
**Course Learning Outcomes**

- Describe key engineering properties and behaviors of commonly encountered geomaterials
- Recognize the key geological factors relevant to dam siting, foundation stability, earthquake hazards, tunnel design, and slope stability
- Identify which earth material behaviors and hazards are relevant to a given engineering geology design problem
- Assess the adequacy of different material characterization and technical analysis tools for investigation of a given engineering geology problem
- Analyze engineering geology problems using methods and tools commonly applied in industry
- Design solutions to mitigate geological risks associated with natural and man-made slopes and underground excavations in rock
- Concisely communicate data collection, data analysis, and design processes and results to a technical audience in written and oral formats using appropriate technical vocabulary and graphical aids

**GEGN573. GEOLOGICAL ENGINEERING SITE INVESTIGATION. 3.0 Semester Hrs.**
Methods of field investigation, testing, and monitoring for geotechnical and hazardous waste sites, including: drilling and sampling methods, sample logging, field testing methods, instrumentation, trench logging,

foundation inspection, engineering stratigraphic column and engineering soils map construction. Projects will include technical writing for investigations (reports, memos, proposals, workplans). Class will culminate in practice conducting simulated investigations (using a computer simulator).

**Course Learning Outcomes**

- No change

**GEGN575. APPLICATIONS OF GEOGRAPHIC INFORMATION SYSTEMS. 0-3 Semester Hr.**

An introduction to Geographic Information Systems (GIS) and their applications to all areas of geology and geological engineering. Lecture topics include: principles of GIS, data structures, digital elevation models, data input and verification, data analysis and spatial modeling, data quality and error propagation, methods of GIS evaluation and selection. Laboratories will use Macintosh and DOS-based personal computer systems for GIS projects, as well as video-presentations. Visits to local GIS laboratories, and field studies will be required. 2 hours lecture, 3 hours lab; 3 semester hours.

**Course Learning Outcomes**

- .

**GEGN578. GIS PROJECT DESIGN. 1-3 Semester Hr.**

(I, II) Project implementation of GIS analysis. Projects may be undertaken by individual students, or small student teams. Documentation of all project design stages, including user needs assessment, implementation procedures, hardware and software selection, data sources and acquisition, and project success assessment. Various GIS software may be used; projects may involve
2-dimensional GIS, 3-dimensional subsurface models, or multi-dimensional time-series analysis. Prerequisite: none. Variable credit, 1-3 semester hours, depending on project. Offered on demand.

**Course Learning Outcomes**

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**GEGN579. PYTHON SCRIPTING FOR GEOGRAPHIC INFORMATION SYSTEMS. 3.0 Semester Hrs.**

(I) Students will learn to use Python scripting with ArcGIS to perform common GIS tasks and to develop their own standalone Python scripts for GIS-based problem solving, automating repetitive or complex geoprocessing work flows, and preparing GIS-based maps. Specific topics include: (1) using Python for basic GIS tasks including field manipulation (e.g. adding, deleting, joining, or calculating fields), file manipulation (e.g., creating, deleting, moving, renaming files), and performing basic spatial analyses; (2) creating stand-alone Python scripts and tools; (3) Using the Python mapping module to control map elements in map layouts; and (4) problem solving to explore more advanced features of Python with ArcGIS. 2 hours lecture, 3 hours lab; 3 semester hours.

**Course Learning Outcomes**

- See GEGN579_Syllabus_2019.

**GEGN580. APPLIED REMOTE SENSING FOR GEOENGINEERING AND GEOSCIENCES. 0-3 Semester Hr.**

This course offers an introduction to remote sensing in general and radar remote sensing and optical remote sensing in specific as well as their applications to all areas of geoengineering and geosciences. Lecture topics include: principles SAR (Synthetic Aperture Radar) and InSAR (Interferometry of Synthetic Aperture Radar) and their applications, as well as basic concepts of optical remote sensing and its application in geoengineering and geosciences. Topics include various sensors and platforms of SAR data acquisition, SAR data access, SAR data processing, data acquisition and processing of optical remote sensing images.

**Course Learning Outcomes**

- 1. Learn basic concepts and principals of SAR and InSAR through classroom lectures and lab exercises. These skills will be of importance in most geosciences and geoengineering careers that you will follow. 2. Learn basic optical remote sensing concepts and principals through classroom lectures and lab exercises. These skills will also be of importance in most geosciences and geoengineering careers that you will follow. 3. Learn and use many skills necessary for project design and planning, as well as ideas and means of facilitating problem solving in science/engineering projects.

**GEGN581. ANALYTICAL HYDROLOGY. 3.0 Semester Hrs.**

Equivalent with GEGN481,
(I) Introduction to the theory, and hydrological application of, probability, statistics, linear algebra, differential equations, numerical analysis, and integral transforms. The course will require more challenging assignments and exams commensurate with graduate credit. Prerequisites: GEGN467. 3 hours lecture; 3 semester hours.

**Course Learning Outcomes**

- To introduce the student to the analysis of many types of hydrologic data using the tools from several mathematics courses, including basic probability and statistics, linear algebra, differential equations, and numerical. The course is also designed to develop the analytic skills necessary to understand and quantify hydrologic processes and problems.
- The class is designed to meet the Hydrologic Science and Engineering admission prerequisite of one semester each of Differential Equations and Probability/Statistics.

**GEGN582. INTEGRATED SURFACE WATER HYDROLOGY. 3.0 Semester Hrs.**

This course provides a quantitative, integrated view of the hydrologic cycle. The movement and behavior of water in the atmosphere (including boundary layer dynamics and precipitation mechanisms), fluxes of water between the atmosphere and land surface (including evaporation, transpiration, precipitation, interception and through fall) and connections between the water and energy balances (including radiation and temperature) are discussed at a range of spatial and temporal scales. Additionally, movement of water along the land surface (overland flow and snow dynamics) and in the subsurface (saturated and unsaturated flow) as well as surface-subsurface exchanges and runoff generation are also covered. Finally, integration and connections within the hydrologic cycle and scaling of river systems are discussed. 3 hours lecture; 3 semester hours.

**Course Learning Outcomes**

- .No change

**GEGN583. MATHEMATICAL MODELING OF GROUNDWATER SYSTEMS. 3.0 Semester Hrs.**

(II) Lectures, assigned readings, and direct computer experience concerning the fundamentals and applications of finite-difference and finite-element numerical methods and analytical solutions to ground water flow and mass transport problems. Prerequisite: A knowledge of FORTRAN programming, mathematics through differential and integral calculus, and GEGN467. 3 hours lecture; 3 semester hours.

**Course Learning Outcomes**

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**GEGN584. FIELD METHODS IN HYDROLOGY. 3.0 Semester Hrs.**
Design and implementation of tests that characterize surface and subsurface hydrologic systems, including data logger programming, sensor calibration, pumping tests, slug tests, infiltration tests, stream gauging and dilution measurements, and geophysical (EM, resistivity, and/or SP) surveys. Prerequisites: Groundwater Engineering (GEGN466, Integrated Surface Water Hydrology (GEGN582) or equivalent classes. 2 hours lecture; 5 hours lab and field exercises one day of the week. Days TBD by instructor; 3 semester hours.
**Course Learning Outcomes**

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**GEGN585. FLUID MECHANICS FOR HYDROLOGY. 2.0 Semester Hrs.**
(I) This class focuses on the fundamental concepts of engineering fluid mechanics as they relate to the study of hydrology. Topics include fluid statics, dynamics, continuity, energy and momentum, dimensional analysis and open channel flow. 2 hours lecture; 2 semester hours.
**Course Learning Outcomes**

- 1. Students will solve problems on fundamental fluid mechanics concepts including hydrostatics, momentum, pressure and flow and energy systems.
- 2. Students will conduct simple dimensional analysis and explain its application to hydrologic research.
- 3. . Students will solve problems related to flow measurement, fluid properties, and fluid statics.
- 4. Students will solve problems related to energy, impulse, and momentum equations.
- 5. Students will solve problems related to pipe and other internal flow.
- 6. Student will explain (or demonstrate or predict or describe or evaluate) how fluid mechanics relates to hydrological systems.

**GEGN585L. INTRODUCTION TO COMPUTATIONAL METHODS IN HYDROLOGY. 1.0 Semester Hr.**
This 1-cr class is a computational lab for the lecture course GEGN/CEEN 585 (Fluid Mechanics for Hydrology). The lab may be taken alone if a Fluid Mechanics lecture course has already been taken. The lab introduces the student to computational platforms and concepts germane to Fluid Mechanics and many other sciences. We use Matlab, Python, and various parallel programming environments to solve problems that use numerical integration, finite-difference solutions of first- and second-order ODEs, random walks to solve advection/diffusion problems, and various statistical concepts. Applications include calculating pressure on a submerged surface, bacterial growth/decay, laminar flow and solute transport between plates, and gradually-varying flow in open channels. Prerequisite: Fluid Mechanics. Co-requisites: GEGN/CEEN 585 Fluid Mechanics for Hydrology.
**Course Learning Outcomes**

- • Design algorithms that can be implemented in modern programming environments including matlab, python, and fortran/openmp • Code useful programs for many different scientific applications, most notably surface water/groundwater hydrology. • Understand and apply concepts needed for parallel computing. • Present code that is readable and editable by others.

**GEGN586. NUMERICAL MODELING OF GEOCHEMICAL SYSTEMS. 3.0 Semester Hrs.**
(II) This course provides quantitative methods for evaluating the geochemical characteristics of geological systems. The course is project based with lectures to provide information about the topic and use of geochemical modeling software. Student projects consist of chemical speciation of waters, activity diagrams, reaction progress models, water-rock interactions, sorption and surface complexation, and kinetic mineral reactions. Students complete an individual project on the geochemical system of their choice and present it to the class. Prerequisite: CEEN550 or CHGC509. 3 hours lecture, 3 semester hours. Offered spring semester, odd years.
**Course Learning Outcomes**

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**GEGN587. HYDROCHEMICAL AND TRANSPORT PROCESSES. 3.0 Semester Hrs.**
(II) Analysis of the chemistry of natural waters in the context of hydrologic systems. The course focuses on sources and dynamic behavior of common natural and anthropogenically introduced solutes of interest, their interactions with minerals, and fate and transport in subsurface and surface environments. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- 1. Evaluate the chemistry of groundwater and surface water samples
- 2. Understand the sources and behavior of common solute of interest in natural systems
- 3. Apply chemical reaction kinetic equations to evaluate the dynamic behavior of common solutes of interest in natural systems
- 4. Evaluate fate and transport of contaminants in surface water and groundwater systems.

**GEGN588. ADVANCED PLANETARY GEOGRAPHIC INFORMATION SYSTEMS. 3.0 Semester Hrs.**
(I, II, S) This course offers a unique opportunity to expand your knowledge and skills in the new and emerging field of planetary mapping and analysis. Upon completing this course, students will possess the knowledge and skills necessary to perform independent planetary GIS tasks, contributing to the advancement of planetary science and space exploration in the student's area of expertise. Throughout the course, we will learn about planetary GIS fundamentals, an overview of historical and contemporary remote sensing space missions, locating open source planetary GIS datasets, organizing GIS data, planetary mapping, geospatial analyses, and digital terrain modeling. We will explore these topics through class discussions, lab exercises, and peer reviews, culminating in an individual planetary GIS project that allows students to investigate a matter of their choosing in-depth. After completing this course, students can locate and integrate planetary GIS datasets for planetary mapping and space resource characterization. Prerequisite: GEGN575, GEGN542, or equivalent. Asynchronous online, 3.0 semester hours. Prerequisite: GEGN575, GEGN432, or equivalent.
**Course Learning Outcomes**

- See GEGN588_Syllabus_9_4_2018.docx

**GEGN590. GIS-BASED REAL WORLD LEARNING PROJECT I - FUNDAMENTALS. 1-6 Semester Hr.**
This course requires a GIS-based project and report that demonstrate competence in the application of GIS to real word problems. The project topic and content of the report is determined by the course instructor, in consultation with the student. The format of the report will follow the

guidelines for a professional journal paper. Variable credit: 1 to 6 credit hours. Repeatable for credit under different topics/experience and the cumulative maximum is 6 credit hours and 3 repeats total.
**Course Learning Outcomes**

- see SYGN588_Syllabus_8_30_2018.docx

**GEGN592. GIS-BASED REAL WORLD LEARNING PROJECT II - ADVANCED APPLICATIONS. 1-6 Semester Hr.**
This course requires a GIS-based project and report that demonstrate competence in the application of GIS to real word problems. The project topic and content of the report is determined by the course instructor, in consultation with the student. The format of the report will follow the guidelines for a professional journal paper. Variable credit: 1 to 6 credit hours. Repeatable for credit under different topics/experience and the cumulative maximum is 6 credit hours and 3 repeats total.
**Course Learning Outcomes**

- see SYGN588_Syllabus-8_30_2018.docx

**GEGN598. SEMINAR IN GEOLOGY OR GEOLOGICAL ENGINEERING. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**GEGN598. SPECIAL TOPICS. 0-6 Semester Hr.**

**GEGN598. SPECIAL TOPICS. 0-6 Semester Hr.**

**GEGN598. SPECIAL TOPICS. 0-6 Semester Hr.**

**GEGN598. SPECIAL TOPICS. 0-6 Semester Hr.**

**GEGN599. INDEPENDENT STUDY IN ENGINEERING GEOLOGY OR ENGINEERING HYDROGEOLOGY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**GEGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

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**GEGN669. ADVANCED TOPICS IN ENGINEERING HYDROGEOLOGY. 1-2 Semester Hr.**
(I, II) Review of current literature and research regarding selected topics in hydrogeology. Group discussion and individual participation. Guest speakers and field trips may be incorporated into the course. Prerequisite: none. 1 to 2 semester hours; may be repeated for credit.

**GEGN670. ADVANCED TOPICS IN GEOLOGICAL ENGINEERING. 3.0 Semester Hrs.**
(I, II) Review of current literature and research regarding selected topics in engineering geology. Group discussion and individual participation. Guest speakers and field trips may be incorporated into the course. Prerequisite: none. 3 hours lecture; 3 semester hours. Repeatable for credit under different topics.
**Course Learning Outcomes**

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**GEGN671. LANDSLIDES: INVESTIGATION, ANALYSIS & MITIGATION. 3.0 Semester Hrs.**
(I) Geological investigation, analysis, and design of natural rock and soil slopes and mitigation of unstable slopes. Topics include landslide types and processes, triggering mechanisms, mechanics of movements, landslide investigation and characterization, monitoring and instrumentation, soil slope stability analysis, rock slope stability analysis, rock fall analysis, stabilization and risk reduction measures. 3 hours lecture; 3 semester hours. Prerequisite: GEGN468, EGGN361, MNGN321, (or equivalents).
**Course Learning Outcomes**

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**GEGN672. ADVANCED GEOTECHNICS. 3.0 Semester Hrs.**
Practical analysis and application of techniques in weak rock engineering, ground-water control in construction, fluvial stabilization and control, earthquake hazard assessment, engineering geology in construction, engineering geology in dam investigation, and other current topics in geotechnics practice. Prerequisite: GEGN468, CEEN312, CEEN312L and MNGN321. 3 hours lecture; 3 semester hours. Offered alternate years.
**Course Learning Outcomes**

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**GEGN673. ADVANCED GEOLOGICAL ENGINEERING DESIGN. 3.0 Semester Hrs.**
(II) Application of geological principles and analytical techniques to solve complex engineering problems related to geology, such as mitigation of natural hazards, stabilization of earth materials, and optimization of construction options. Design tools to be covered will include problem solving techniques, optimization, reliability, maintainability, and economic analysis. Students will complete independent and group design projects, as well as a case analysis of a design failure. 3 hours lecture; 3 semester hours. Offered alternate years.
**Course Learning Outcomes**

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**GEGN681. VADOSE ZONE HYDROLOGY. 3.0 Semester Hrs.**
(II) Study of the physics of unsaturated groundwater flow and contaminant transport. Fundamental processes and data collection methods will be presented. The emphasis will be on analytic solutions to the unsaturated flow equations and analysis of field data. Application to non-miscible fluids, such as gasoline, will be made. The fate of leaks from underground tanks will be analyzed. Prerequisites: GEGN467 or equivalent; Math through Differential Equations. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

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**GEGN682. FLOW AND TRANSPORT IN FRACTURED ROCK. 3.0 Semester Hrs.**
(I) Explores the application of hydrologic and engineering principles to flow and transport in fractured rock. Emphasis is on analysis of field data and the differences between flow and transport in porous media and fractured rock. Teams work together throughout the semester to solve problems using field data, collect and analyze field data, and do independent research in flow and transport in fractured rock. 3 hours lecture; 3 credit hours. Prerequisite: GEGN581.
**Course Learning Outcomes**

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**GEGN683. ADVANCED GROUND WATER MODELING. 3.0 Semester Hrs.**
(II) Flow and solute transport modeling including: 1) advanced analytical modeling methods; 2) finite elements, random-walk, and method of characteristics numerical methods; 3) discussion of alternative computer codes for modeling and presentation of the essential features of a number of codes; 4) study of selection of appropriate computer codes for specific modeling problems; 5) application of models to ground water problems; and 6) study of completed modeling projects through literature review, reading and discussion. Prerequisite: GEGN509/CHGC509 or GEGN583. 2 hours lecture, 3 hours lab; 3 semester hours.
**Course Learning Outcomes**

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**GEGN698. SPECIAL TOPICS. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**GEGN699. INDEPENDENT STUDY IN ENGINEERING GEOLOGY OR ENGINEERING HYDROGEOLOGY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**GEGN707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.**
(I, II, S) Research credit hours required for completion of a Masters-level thesis or Doctoral dissertation. Research must be carried out under the direct supervision of the student's faculty advisor. Variable class and semester hours. Repeatable for credit.
**Course Learning Outcomes**

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**GEGX571. GEOCHEMICAL EXPLORATION. 3.0 Semester Hrs.**
(II) Dispersion of trace metals from mineral deposits and their discovery. Laboratory consists of analysis and statistical interpretation of data of soils, stream sediments, vegetation, and rock in connection with field problems. Term report required. 2 hours lecture, 3 hours lab; 3 semester hours. Prerequisite: none.
**Course Learning Outcomes**

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**GEOL501. APPLIED STRATIGRAPHY. 0-4 Semester Hr.**
(I) Review of basic concepts in siliciclastic and carbonate sedimentology and stratigraphy. Introduction to advanced concepts and their application to exploration and development of fossil fuels and stratiform mineral deposits. Modern facies models and sequence-stratigraphic concepts applied to solving stratigraphic problems in field and subsurface settings. Prerequisites: GEOL314 or equivalent. 3 hours lecture, 4 hours lab; 4 semester hours.
**Course Learning Outcomes**

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**GEOL502. STRUCTURAL METHODS FOR SEISMIC INTERPRETATION. 3.0 Semester Hrs.**
(I) A practical course that covers the wide variety of structural methods and techniques that are essential to produce a valid and coherent interpretation of 2D and 3D seismic reflection data in structurally complex areas. Topics covered include: Extensional tectonics, fold and thrust belts, salt tectonics, inversion tectonics and strike-slip fault systems. Laboratory exercises are based on seismic datasets from a wide variety of structural regimes from across the globe. The course includes a 4 day field trip to SE Utah. Prerequisite: GEOL309 and GEOL314 or GEOL315, or equivalents. 3 hours lecture/lab; 3 semester hours.
**Course Learning Outcomes**

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**GEOL503. INTEGRATED GEOLOGICAL INTERPRETATION OF 3D SEISMIC DATA. 3.0 Semester Hrs.**
(II) INTEGRATED GEOLOGICAL INTERPRETATION OF 3D SEISMIC DATA-A PRACTICAL COURSE IN SEISMIC INTERPRETATION OF GLOBAL DATASETS. A practical course in workstation based, integrated geological interpretation of 3D seismic reflection data. Course builds directly on the seismic interpretation skills learnt in the prerequisite GEOL502 Structural Methods for Seismic Interpretation. Key concepts developed in this course are: making internally consistent interpretations of complex 3D datasets and developing integrated geological (structural and stratigraphic) interpretations of 3D seismic data. Prerequisite: GEOL502. 3 hours lecture/lab; 3 semester hours.
**Course Learning Outcomes**

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**GEOL504. UNCERTAINTY IN GEOSCIENCES. 3.0 Semester Hrs.**
In this fully online course you will learn to identify, assess and communicate uncertainty and bias in geosciences. This course provides pragmatic skills for uncertainty assessment and communication in industry and academia, with the aim to improve resource industry effectiveness and academic advancement of knowledge. The course includes video presentations from industry professionals and academics across the geological disciplines and industries. Learning methods are focused on projects, discussions and reflection.
**Course Learning Outcomes**

- After the successful completion of this course students will be able to: 1. identify and accept sources of uncertainty in geoscience 2. Synthesize the sources and types of uncertainties as linked to data collection, analyses and interpretation in different geoscience disciplines 3. Assess the effects of uncertainty in academic and industry settings, including the effects of uncertainty on the advancement of knowledge and the effectiveness of resource

industry 4. Critique uncertainty assessment, or the lack thereof, in industry and academic applications 5. Apprise solutions for reducing uncertainty as related to uncertainty types and sources 6. Design uncertainty assessment and reduction strategies that are relevant for your professional or academic discipline 7. Communicate uncertainty to a wide range of audiences clearly and effectively

**GEOL505. ADVANCED STRUCTURAL GEOLOGY. 3.0 Semester Hrs.**
(I) Advanced Structural Geology builds on basic undergraduate Structural Geology. Structures such as folds, faults, foliations, lineations and shear zones will be considered in detail. The course
focuses on microstructures, complex geometries and multiple generations of deformation. The laboratory consists of microscopy, in-class problems, and some field-based problems. Prerequisites: GEGN307, GEOL309, GEGN316, GEOL321, or equivalents. 2 hours lecture, 2 hours lab, and field exercise; 3 semester hours.
**Course Learning Outcomes**

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**GEOL508. SKARNS AND RELATED DEPOSITS. 3.0 Semester Hrs.**
Skarn deposits are one of the most common deposit types in the world. They are the largest source of W and Sn, and also a significant source of Au, Ag, B, Cu, Fe, Mo, Pb, Zn, Pb, Mo, plus U, REE and other rare metals. This course will introduce to students all aspects of skarns and skarn deposits, including the geological features (e.g., geological context, host rock packages, alteration assemblages, mineralization styles, paragenesis and zonations), formation processes and evolution (e.g., magma fertility, magma-hydrothermal transition, fluid composition, fluid-rock reactions, plus metal sources, transportation, deposition and enrichment), investigation and research methods, the relationship between skarns and other types of deposits (porphyry, epithermal, carbonate replacement, Carlin type, SEDEX, MVT, VHMS, orogenic, and IOCG deposits), and exploration methods. The course has a significant lab/field skill component with representative skarn samples from all over the world and intensive hands-on training on skarn alteration-mineralization and texture recognization and interpretation, plus a field trip to one of the skarns in Colorado or nearby states. Prerequisites: GEGN307, GEGN316, GEGN401 and GEOL321.
**Course Learning Outcomes**

- Capacity to make accurate, efficient, and critical geological observations and document the observations into maps, cross-sections, and reports/publications. Be familiar with various field and laboratory tools and methods, and know what methods to use for what purposes. The objects of observation and documentation includes igneous rocks, wallrocks, alteration and mineralization mineralogy, texture, paragenesis, spatial zonation, ages of events, rock and mineral compositions (major + trace elements), isotopic features, spectral feature, and fluid properties. Be able to make sampling strategies and take samples for laboratory analyses and studies.
- Capacity to infer formation conditions based on the observations, including the temperature, pressure, redox state, pH, fluid source, fluid compositions, rock mechanical properties (brittle vs. ductile), conditions for fluid flow (e.g., rock permeability, potential fluid channel), and fluid-rock reactions.
- Capability of critical thinking to, based on the observations and inferred conditions, predict the architecture of the skarn system and estimate the position of orebodies, to reconstruct the formation processes, and/or to make hypotheses and design tests/further investigation to verify or reject the hypotheses.
- The course contributes to the program goals in enriching students with mineral deposit knowledge and understanding, and enhancing students' skills and capacities in mineral exploration, because skarn deposits are one of the most common and important deposit types in the world.

**GEOL512. MINERALOGY AND CRYSTAL CHEMISTRY. 3.0 Semester Hrs.**
(I) Relationships among mineral chemistry, structure, crystallography, and physical properties. Systematic treatments of structural representation, defects, mineral stability and phase transitions, solid solutions, substitution mechanisms, and advanced methods of mineral identification and characterization. Applications of principles using petrological and environmental examples. Prerequisites: GEOL321, DCGN209 or equivalent. 2 hours lecture, 3 hours
lab; 3 semester hours. Offered alternate years.
**Course Learning Outcomes**

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**GEOL513. HYDROTHERMAL GEOCHEMISTRY. 3.0 Semester Hrs.**
Equivalent with CHGC513,
Geochemistry of high-temperature aqueous systems. Examines fundamental phase relationships in model systems at elevated temperatures and pressures. Major and trace element behavior during fluid-rock interaction. Theory and application of stable isotopes as applied to hydrothermal mineral deposits. Review of the origin of hydrothermal fluids and mechanisms of transport and deposition of ore minerals. Includes the study of the geochemistry of magmatic aqueous systems, geothermal systems, and submarine hydrothermal vents. Prerequisites: GEGN401 or GEOL524.
**Course Learning Outcomes**

- No changes

**GEOL514. BUSINESS OF ECONOMIC GEOLOGY. 3.0 Semester Hrs.**
Examines the business side of mineral exploration including company structure, fundraising, stock market rules and regulations, and legal environment. Reviews the types of minerals exploration companies, differences between mineral sectors, rules and practices of listing a minerals company on a stock exchange, and legal requirements of listing and presenting data to stockholders. The course is centered on lectures by industry representatives from the Denver area. Includes participation in a technical conference in Vancouver or Toronto and meetings with lawyers, stockbrokers, and geoscientists working in the mineral industry. Prerequisites: GEGN401. 3 hours lecture and seminar; 3 semester hours. Offered alternate years when student demand is sufficient.
**Course Learning Outcomes**

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**GEOL515. ADVANCED MINERAL DEPOSITS. 2.0 Semester Hrs.**
Geology of mineral systems at a deposit, district, and regional scale formed by magmatic, hydrothermal, sedimentary/basinal, and metamorphic processes. Emphasis will be placed on a systems approach to evaluating metal sources, transportation paths, and traps. The system examined will vary by year. Repeatable for credit.
**Course Learning Outcomes**

**GEOL517. DRILL CORE LOGGING FOR ECONOMIC GEOLOGY. 2.0 Semester Hrs.**
(I, II) Methods of diamond drill core logging related to mineral exploration. Documentation of lithology, alteration, structural geology, and

mineralization. Drill core from different deposit types is utilized. Sampling strategies for geochemical analysis and rock quality designation are discussed. Participants prepare technical reports for each drill hole logged. 2 semester hours.

**Course Learning Outcomes**

- Methods of drill core logging related to mineral exploration.

**GEOL518. MINERAL EXPLORATION. 3.0 Semester Hrs.**

(II) Mineral industry overview, deposit economics, target selection, deposit modeling, exploration technology, international exploration, environmental issues, program planning, proposal development. Team development and presentation of an exploration proposal. Prerequisite: GEOL515, GEOL520, or equivalent. 2 hours lecture/seminar, 3 hours lab; 3 semester hours. Offered when student demand is sufficient.

**Course Learning Outcomes**

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**GEOL519. ORE DEPOSITS OF THE WESTERN US. 2.0 Semester Hrs.**

(I, II, S) Methods of field practices related to mineral exploration and mining. Regional and deposit-scale geology, including epithermal deposits and porphyry deposits. Includes mineral prospect evaluation, structural geology, physical volcanology, deposit definition, alteration mapping, mining methods, and ore processing. Core logging, mapping, lithogeochemical sampling, and mine visits. Course involves a seminar that focuses on the geology and deposit types in the area to be visited and an intense multi-day field trip. Each day in the field includes up to 4 hours of instruction and 4 hours of team-oriented field exercises. 2 semester hours.

**Course Learning Outcomes**

- Methods of field practices related to mineral exploration. Mineral prospect evaluation, structural geology, physical volcanology, deposit definition, alteration mapping, mining methods, and ore processing.

**GEOL520. NEW DEVELOPMENTS IN THE GEOLOGY AND EXPLORATION OF ORE DEPOSITS. 2.0 Semester Hrs.**

Each topic unique and focused on a specific mineral deposit type or timely aspects of economic geology. Review of the geological and geographic setting of a specific magmatic, hydrothermal, or sedimentary mineral deposit type. Detailed study of the physical and chemical characteristics of selected deposits and mining districts. Theory and application of geological field methods and geochemical investigations. Includes a discussion of genetic models, exploration strategies, and mining methods. Prerequisite: GEGN401. 2 hours lecture; 2 semester hours.

**Course Learning Outcomes**

- Apply knowledge of geological field methods and investigations.

**GEOL521. FIELD AND ORE DEPOSIT GEOLOGY. 3.0 Semester Hrs.**

(I, S) Field study of major mineral deposit districts inside and outside of the USA. Examines regional and deposit-scale geology. Underground and open pit mine visits and regional traverses. Topics addressed include deposit definition, structural geology, alteration mapping, mining methods, and ore processing. Course involves a seminar in the spring semester that focuses on the geology and deposit types in the area to be visited. An intense 10-14 day field trip is run in the summer semester. Prerequisites: none. 6 hours lab and seminar; 2 semester hours in spring, 1 semester hour in summer. Offered alternate years when student demand is sufficient. Repeatable for credit.

**Course Learning Outcomes**

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**GEOL522. TECTONICS AND SEDIMENTATION. 3.0 Semester Hrs.**

Application and integration of advanced sedimentologic and stratigraphic concepts to understand crustal deformation at a wide range of spatial- and time-scales. Key concepts include: growth-strata analysis, interpretation of detrital composition (conglomerate unroofing sequences and sandstone provenance trends), paleocurrent deflection and thinning trends, tectonic control on facies distribution and basic detrital zircon and fission track analysis. Students will read a
wide range of literature to explore the utility and limitation of traditional "tectonic signatures" in stratigraphy, and will work on outcrop and subsurface datasets to master these concepts. Special attention is paid to fold-thrust belt, extensional and salt-related deformation. The course has important applications in Petroleum Geology, Geologic Hazards, and Hydrogeology. Required: 2-3 fieldtrips, class presentations, and a final paper that is written in a peer-reviewed journal format. Prerequisites: GEOL314 or equivalent, and GEOL309 or equivalent. 3 hours lecture and seminar; 3 semester hours. Offered even years.

**Course Learning Outcomes**

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**GEOL523. REFLECTED LIGHT AND ELECTRON MICROSCOPY. 2.0 Semester Hrs.**

(I) Theoretical and practical aspects of reflected light and electron microscopy. Emphasis will be placed on applications to ore deposit exploration and research. Lecture and discussion topics will highlight both standard and new techniques and instrumentation including SEM and QEMSCAN, as well as key questions in mineral deposit genesis which can be addressed using reflected light and electron microscopy. Includes detailed study of a selected suite of samples, with emphasis on mineral identification, textural relationships, paragenetic sequences, and mineral chemistry. Course culminates in a project. Prerequisites: GEGN401. 1 hour lecture; 3 hours lab; 2 semester hours.

**Course Learning Outcomes**

- n/a

**GEOL524. ORE DEPOSIT MODELS AND EXPLORATION STRATEGIES. 3.0 Semester Hrs.**

(I) Provides an up-to-date synopsis of the geological settings and characteristics of the major types of magmatic, hydrothermal, and sedimentary metallic ore deposits. Emphasis is placed on the discussion of the source of metals, their transport, and the physical and chemical factors controlling the deposition of metallic ores in different geological environments. Exploration strategies are discussed for each deposit type. Laboratory consists of hand specimen study of host rock and ore mineral suites, optical microscopy, interpretation of phase diagrams, drill core logging, and open pit and underground field investigations. Lectures and laboratories are accompanied by assigned reading. 2 hours lecture; 3 hours lab; 3 semester hours.

**Course Learning Outcomes**

- 1. Have an understanding of fundamental principles of ore deposit genesis; 2. Will understand ore deposit classification; 3. Will understand which commodities are mined from which deposit types; 4. Will understand ore deposit models for the most important deposit types; 5. Will understand key phase diagrams required to explain the mineralogy of ore deposits and alteration halos; 6. Will have gained experience in drill core logging and underground mapping; 7. Will

have better writing skills; 8. Will have been exposed to principles of ore deposit research; 9. Will understand the publication process and; 10. Will have gained insights into the exploration and mining industry.

**GEOL525. PRINCIPLES OF METAMORPHIC GEOLOGY. 3.0 Semester Hrs.**
Study of metamorphic processes and products that occur on Earth at the micro- to the macro-scale. Areas of focus include (a) the nature of metamorphism in subduction zones and continental interiors, (b) the mechanisms and physico-chemical effects of fluid-rock and melt-rock interactions, (c) links between metamorphism and ore-forming processes, and (d) combining metamorphism with geochemistry, isotope geochronology, and structural geology to quantify the tectonothermal evolution of the lithosphere throughout space and time. Laboratory exercises emphasize the examination, identification, and interpretation of metamorphic minerals and microstructures in hand sample and down the microscope, and the calculation and application of thermodynamically constrained phase equilibria to describe and predict the pressure-temperature evolution of rocks and terranes. Short field excursions to local sites of metamorphic interest. Offered every other year. Prerequisites: GEOL321 and GEGN307. 2 hours lecture; 3 hours lab; 3 semester hours.
**Course Learning Outcomes**

- 1) Demonstration of exemplary disciplinary expertise. 2) Demonstration of a set of professional skills necessary to succeed in a student's chosen career path.

**GEOL526. PLATE TECTONICS. 3.0 Semester Hrs.**
Introduction to the theory of plate tectonics as a first-order framework with which the evolution of the Earth's lithosphere in space and time may be described and understood. Key topics include plate boundaries, the mechanisms of mountain building, crustal growth and destruction, volcanism and seismicity in intraplate and plate-margin settings, and secular changes in plate tectonic processes and products over geological time. Formation of all rocks types (igneous, sedimentary, metamorphic) will be discussed in the context of plate tectonics. Other planets and planetary processes will be discussed and compared to Earth. Prerequisite: Basic geology knowledge; Consent from instructor.
**Course Learning Outcomes**

- Students will: 1. Explore geophysical techniques, to learn about the layers of the earth 2. Be able to reconstruct plate motions based on paleomagnetic data 3. Predict plate motions and tectonic processes based on current or given pate boundaries and their orientations, and plate velocities and directions 4. Interpret and predict processes at convergent, divergent and transform plate boundaries 5. Use seismic data to interpret fault motions during earthquakes 6. Debate when plate tectonics started on Earth 7. Explore other planets and interpret geologic processes from available imagery 8. Interpret and predict the relationship between plate tectonics, and earth resources, climate, life on earth and other relevant processes

**GEOL527. SWIR (SHORT WAVELENGTH INFRA-RED) SPECTRAL ANALYSIS. 1.0 Semester Hr.**
SWIR (Short Wavelength Infra-Red) spectral analysis is an efficient way to clay minerals and other minerals containing H2O, OH-, CO32-, and ammonia. The numerical spectral values are useful in inferring mineral compositions and formation conditions, plus revealing spatial trends, which helps to understand mineral deposits and facilitate mineral exploration. This course will train to students on how to use portable SWIR instruments to make measurements, then how to interpret the spectra to identify clay and other minerals containing H2O, OH-, CO32-, and ammonia, and to extract numerical values of spectral features, plus the geological implications of these values, and how to reveal spatial trends in those values. 0.7 hours lecture, 0.9 hours lab; 1 semester hour. Prerequisite: GEOL 321 Mineralogy and mineral characterization, GEGN401 Mineral Deposits. Co-requisite: NA.
**Course Learning Outcomes**

- Capacity to take measurements using SWIR instruments.
- Capacity to identify clay and other hydrous minerals and to extract numerical values of spectral features from SWIR spectra.
- Capacity to infer the geological implications (e.g., compositions and formation temperatures of certain minerals) and to reveal spatial trends.
- Graduate Profile

**GEOL528. MINING GEOLOGY. 3.0 Semester Hrs.**
Role of geology and the geologist in the development and production stages of a mining operation. Topics addressed: mining operation sequence, mine mapping, drilling, sampling, reserve estimation, economic evaluation, permitting, support functions. Field trips, mine mapping, data evaluation, exercises and term project. 2 hours lecture/seminar, 3 hours laboratory: 3 semester hours. Offered in even years.
**Course Learning Outcomes**

- No changes

**GEOL535. LITHO ORE FORMING PROCESSES. 1.0 Semester Hr.**
Lithogeochemistry is the study of fluid-rock interaction in hydrothermal systems from a mineralogical perspective. Practical 1 credit seminar course were we review mechanisms of metal complexation, transport and mineralization processes in hydrothermal fluids and how they are connected to mineral alteration textures, mineral/rock geochemistry and mineral paragenesis. Students will combine observations of mineral assemblages in rocks and thin sections, and geochemical data to link this knowledge to field observations. The tools provided by this course will enable students to recognize alteration types, establish a mineral paragenesis, and connect alteration features with geochemical changes in bulk rock and mineral chemistry in ore deposits. An extra day will be spent in the field to visit a historic mining district in Colorado. The seminar course comprise also discussions and readings of recent articles and a brief review of hydrothermal-(magmatic) ore deposits (e.g. Greisen alteration, epithermal and porphyry systems, REE and critical metal deposits in (per)alkaline systems, Pb-Zn MVT type deposits). Prerequisite: GEOL321, GEGN401.
**Course Learning Outcomes**

- Present and critically examine research articles.
- Predict mineral stabilities and metal transport in hydrothermal fluids using the program GEM-Selektor.
- Recognize rock alteration types and establish a mineral paragenesis for different ore deposits.
- Interpret geochemical changes in bulk rock and mineral chemistry.
- Analyze results from mineral and bulk rock chemical data.
- Write reports and critically evaluate results from numerical modeling.

**GEOL540. ISOTOPE GEOCHEMISTRY AND GEOCHRONOLOGY. 3.0 Semester Hrs.**
(II) A study of the principles of geochronology and stable isotope distributions with an emphasis on the application of these principles to important case studies in igneous petrology and the formation of ore deposits. U, Th, and Pb isotopes, K-Ar, Rb-Sr, oxygen isotopes,

hydrogen isotopes, and carbon isotopes included. Prerequisite: none. 3 hours lecture; 3 semester hours. Offered alternate years.
**Course Learning Outcomes**

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**GEOL550. INTEGRATED BASIN MODELING. 3.0 Semester Hrs.**
(I) This course introduces students to principal methods in computer-based basin modeling: structural modeling and tectonic restoration; thermal modeling and hydrocarbon generation; and stratigraphic modeling. Students apply techniques to real data set that includes seismic and well data and learn to integrate results from multiple approaches in interpreting a basin's history. The course is primarily a lab course. Prerequisite: none. A course background in structural geology, sedimentology/stratigraphy or organic geochemistry will be helpful. 1 hour lecture, 5 hours labs; 3 semester hours.
**Course Learning Outcomes**

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**GEOL551. APPLIED PETROLEUM GEOLOGY. 3.0 Semester Hrs.**
Subjects to be covered include computer subsurface mapping and cross sections, petrophysical analysis of well data, digitizing well logs, analyzing production decline curves, creating hydrocarbon-porosity-thickness maps, volumetric calculations, seismic structural and stratigraphic mapping techniques, and basin modeling of hydrocarbon generation. Students are exposed to three software packages used extensively by the oil and gas industry. Prerequisite: GEGN438 or GEOL609. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

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**GEOL552. UNCONVENTIONAL PETROLEUM SYSTEMS. 3.0 Semester Hrs.**
Unconventional petroleum systems have emerged as a critical and indispensable part of current US production and potential future reserves. Each of the 5 unconventional oil and 4 unconventional gas systems will be discussed: what are they, world wide examples, required technology to evaluate and produce, environmental issues, and production/resource numbers. The oil part of the course will be followed by looking at cores from these systems. The gas part of the course will include a field trip to the Denver, Eagle, and Piceance Basins in Colorado to see outstanding outcrops of actual producing units. Prerequisites: GEGN438 or GEOL609, GEGN527. 3 hours lecture; 3 semester hours. Offered alternate years.
**Course Learning Outcomes**

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**GEOL553. GEOLOGY AND SEISMIC SIGNATURES OF RESERVOIR SYSTEMS. 3.0 Semester Hrs.**
This course is a comprehensive look at the depositional models, log signatures, characteristics, and seismic signatures for all the main reservoirs we explore for and produce from in the subsurface. The first half is devoted to the clastic reservoirs (12 in all); the second part to the carbonate reservoirs (7 total). The course will utilize many hands-on exercises using actual seismic lines for the various reservoir types. Prerequisites: GEOL501 or GEOL314. 3 hours lecture; 3 semester hours. Offered alternate years.
**Course Learning Outcomes**

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**GEOL555. STRUCTURAL FIELD RESEARCH. 4.0 Semester Hrs.**
(I) This course focuses on geological field work along the Colorado Front Range through inquiry-based research and hypothesis-testing. The type of problems students will work on will vary from more applied problems (e.g. centered around the Edgar mine) or more academic/scientific orientated problems, depending on the student's interest. The class will be split up in groups of students with similar interests. In the first part of the course, we take an introductory two-day field trip, and students will review existing literature and maps and write a brief research proposal including hypotheses, tests and a work plan for the remainder of the course. The second part of the course will focus on field work. During the last part of the course, students prepare a geological map and appropriate cross sections, and a report presenting rock descriptions, structural analysis, a geological history, and interpretation of results in the context of the hypotheses posed. Prerequisites: (need previous field experience such as a field course, and a course in structural geology and one in earth materials). 2 hours lecture, 6 hours lab; 4 semester hours.
**Course Learning Outcomes**

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**GEOL556. VIRTUAL STRUCTURAL FIELD MAPPING. 1.0 Semester Hr.**
This exercise takes students to Rhoscolyn, Anglesey, NW Wales, virtually. Students acquire some of the interpretative and associated technique-oriented skills involved via a 'virtual approach' that exploits traditional photography and modern computer ('gaming') opportunities, linked to the provision of relevant field data. This course gives a unique opportunity to visit Rhoscolyn in Wales, to map and analyze structures, including folds and bedding/cleavage relationships that will be useful to those working in mining, petroleum, or academia. Prerequisite: Structural geology knowledge; Consent from instructor .
**Course Learning Outcomes**

- At the completion of this course, students will be able to: • Apply field-based skills such as (1) map construction from field data including boundary projection techniques, (2) true-profile cross-section construction, (3) stereographic projection, (4) keeping accurate field notes and sketches. • Interpret progressive and polyphase deformation in the field area based on mapping and structural analysis • Write a detailed outline of the progressive and/or polyphase geological evolution of the field area, with statements of your field observations that support each event, with reference to appropriate geologic map, cross section, stereographic projection, etc.

**GEOL557. EARTH RESOURCE DATA SCIENCE 1: FUNDAMENTALS. 3.0 Semester Hrs.**
A hands-on course intended to introduce basic concepts of data science as it pertains to managing surface and subsurface Earth resources, and give examples that can be used in daily geoscience workflows.
**Course Learning Outcomes**

- A hands-on course intended to introduce basic concepts of data science as it pertains to managing surface and subsurface Earth resources, and give examples that can be used in daily geoscience workflows.

**GEOL558. EARTH RESOURCE DATA SCIENCE 2: APPLICATIONS AND MACHINE-LEARNING. 3.0 Semester Hrs.**
Introduction to specific applications (use cases) for Earth resource data science, with examples from the petroleum and minerals industries as well as water resource monitoring and remote-sensing of Earth change.

Students are encouraged to provide their own datasets to enable real-world application of the concepts discussed. Prerequisites: GEOL557.
**Course Learning Outcomes**

- Introduction to specific applications (use cases) for Earth resource data science, with examples from the petroleum and minerals industries as well as water resource monitoring and remote-sensing of Earth change. Students are encouraged to provide their own datasets to enable real-world application of the concepts discussed.

**GEOL559. APPLIED STRUCTURAL FIELD MAPPING. 2.0 Semester Hrs.**
Students will take their knowledge and skills from Virtual Structural Field Mapping, or equivalent, to the field, map an area, and receive feedback on deliverables from other students and the instructor along the way through two rounds of submission and peer review. Students will get to know each other and will build a network for the future that will be an invaluable resource to find and provide help beyond this course. Prerequisite: GEOL556. Co-requisite: GEOL556.
**Course Learning Outcomes**

- This course will consist of the following components, where students will not only learn to map independently, but also to incorporate comments by their peers and instructors, and to provide valuable constructive feedback to their peers. 1. Design a semester plan for structural mapping and analysis 2. Construct a map and cross section and use stereographic projection 3. Interpret the structural history of the map area and its implications 4. Provide critical and constructive evaluations of structural maps and analyses provided by others To accomplish the above outcomes, you will: 1. students make a plan for what they want to map and at what scale 2. map for ~30 hours over five weeks and submit a (preliminary) map, cross section, structural analysis and report 3. do a peer review of two others in the course, where students will see how others are doing what they are doing, learn about each other’s areas, see what works and what doesn't, provide feedback, discuss, and (perhaps most importantly) create community between mappers so they can help each other in the future. 4. the instructor gives them individual feedback, and students and instructor meet as a group to discuss what was learned. 5. second round of mapping for ~30 hours over five weeks and submit a final map, cross section, and structural analysis, plus a writeup of the geological history and potential controls on mineral deposits and locations thereof in their area. 6. second round of peer review (students will give feedback of two different class mates in the course than before) 7. the instructor gives them individual feedback, and students and instructor meet as a group to discuss what was learned.

**GEOL560. IMPERIAL BARREL AAPG COMPETITION CLASS. 3.0 Semester Hrs.**
(II) The course is designed for geoscience students to evaluate as a team a geophysical and geological dataset. The date set consists of seismic, well data, geochemical information, and geophysical logs. The class provides students with an insight into the hydrocarbon exploration business. A petroleum geology background is useful but not required. A team will compete at the Rocky Mountain Section competition and go onto the Annual American Association of Petroleum Geologist (AAPG) meeting competition if they win the section competition. The class is intended for graduate students only. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Evaluate as a team a geophyiscal and geological dataset (seismic, well data, geochemical information, and geophysical logs).
- The class provides students with an insight into the hydrocarbon exploration business.

**GEOL565. RISKS AND VOLUMES ASSESSMENT FOR CONVENTIONAL AND UNCONVENTIONAL PROSPECTS AND PLAYS. 3.0 Semester Hrs.**
(II) Students learn to translate geological knowledge into sound and realistic numbers and ranges for consistent risk and volume assessment of exploration prospects. Prerequisite: GEGN438. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- 1. Estimate geological risks for conventional and unconventional exploration prospects.
- 2. Calculate deterministic volumes of petroleum in exploration prospects.
- 3. Assess the range of input parameters for volumetric calculations.
- 4. Calculate probabilistic volumes of petroleum in exploration prospects.
- 5. Use industry-standard software (REP, GeoX, or both) to run Monte-Carlo simulations to estimate risks and volumes for exploration segments, prospects and wells.
- 6. Use dependencies between segments to estimate risked prospect volumes.
- 7. Aggregate prospects into exploration portfolio.

**GEOL570. APPLICATIONS OF SATELLITE REMOTE SENSING. 3.0 Semester Hrs.**
(II) An introduction to geoscience applications of satellite remote sensing of the Earth and planets. The lectures provide background on satellites, sensors, methodology, and diverse applications. Topics include visible, near infrared, and thermal infrared passive sensing, active microwave and radio sensing, and geodetic remote sensing. Lectures and labs involve use of data from a variety of instruments, as several applications to problems in the Earth and planetary sciences are presented. Students will complete independent term projects that are presented both written and orally at the end of the term. Prerequisites: PHGN200 and MATH225. 2 hours lecture, 2 hours lab; 3 semester hours.
**Course Learning Outcomes**

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**GEOL575. PETROLEUM SYSTEMS ANALYSIS. 3.0 Semester Hrs.**
(I, II, S) The goal is to learn how to analyze petroleum systems and use tools of petroleum geochemistry and basin modeling to find, appraise and produce oil and gas. Prerequisites: GEGN438. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- 1) Demonstration of exemplary disciplinary expertise. 2) Demonstration of a set of professional skills necessary to succeed in a student's chosen career path.

**GEOL585. APPLICATION OF SEISMIC GEOMORPHOLOGY. 3.0 Semester Hrs.**
(I) Seismic Geomorphology is the study of landforms imaged in 3-D seismic data, for the purpose of understanding the history, processes and fill architecture of a basin. This course will review both qualitative and quantitative approaches to interpreting and applying seismic geomorphologic observations in basin exploration and development. Examples from Gulf of Mexico, Indonesia, Trinidad, Morocco, New Zealand and other basins of the world will be used to illustrate the

techniques for interpreting the depositional elements of fluvial, deltaic, shoreline, shelf, deep water clastic systems, as well as delineating geohazards, and for quantifying and using those data to predict reservoir distribution and architecture, body geometries, planning field developments and assessing uncertainty. This introductory look at the tool of seismic geomorphology is suitable for any geoscientists or engineers looking to enhance their understanding of ancient depositional systems imaged in seismic data. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- This course will review both qualitative and quantitative approaches to interpreting and applying seismic geomorphologic observations in basin exploration and development.
- Introductory look at the tool of seismic geomorphology suitable for any geoscientist or engineer looking to enhance understanding of ancient depositional systems imaged in seismic data.

**GEOL597. SPECIAL SUMMER COURSE. 0-15 Semester Hr.**

**GEOL597. SPECIAL SUMMER COURSE. 0-15 Semester Hr.**

**GEOL598. SEMINAR IN GEOLOGY OR GEOLOGICAL ENGINEERING. 0-3 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**GEOL598. SPECIAL TOPICS. 0-6 Semester Hr.**

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**GEOL598. SPECIAL TOPICS. 0-6 Semester Hr.**

**GEOL598LA. SPECIAL TOPICS LAB. 0-6 Semester Hr.**

**GEOL598LB. SPECIAL TOPICS LAB. 0-6 Semester Hr.**

**GEOL599. INDEPENDENT STUDY IN GEOLOGY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**GEOL599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

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**GEOL601. CORE TO OUTCROP STRATIGRAPHY. 2.0 Semester Hrs.**
(II) A seminar series integrating core and outcrop observations with class discussions. Topics range from global to regional scale tectono-stratigraphy to process sedimentology. Discussions are based on reading journal papers combined with core observations. Field trip encompasses a series of outcrop-based projects/exercises. Prerequisite: GEOL501. 2 hours seminar; 2 semester hours.
**Course Learning Outcomes**

- 1) Demonstration of exemplary disciplinary expertise. 2) Demonstration of a set of professional skills necessary to succeed in a student's chosen career path.

**GEOL608. HISTORY OF GEOLOGICAL CONCEPTS. 3.0 Semester Hrs.**
(I) Lectures and seminars concerning the history and philosophy of the science of geology; emphasis on the historical development of basic geologic concepts. Course is an elective for doctoral candidates in department. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- No change

**GEOL609. ADVANCED PETROLEUM GEOLOGY. 3.0 Semester Hrs.**
(I) Subjects to be covered involve consideration of basic chemical, physical, biological and geological processes and their relation to modern concepts of oil/gas generation (including source rock deposition and maturation), and migration/accumulation (including that occurring under

hydrodynamic conditions). Concepts will be applied to the historic and predictive occurrence of oil/gas to specific Rocky Mountain areas. In addition to lecture attendance, course work involves review of topical papers and solution of typical problems. 3 hours lecture; 3 semester hours. Prerequisite: GEGN438.
**Course Learning Outcomes**

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**GEOL610. ADVANCED SEDIMENTOLOGY. 3.0 Semester Hrs.**
Keynote lectures, mixed with discussions, in-class exercises, core and field observations in a seminar series on sedimentology. Introduction to current hot topics in sedimentology, and discussions on fundamental principles. Specific topics vary yearly depending on most recent advancements and course participant's interests. Quantitative sedimentology. Applications of sedimentology. All seminars are based on reading and discussing journal papers. Field trip to a modern environment. Essays and presentations required. Prerequisite: GEOL501. Acceptable to take GEOL610 at the same time, as GEOL501. 3 hours lecture and seminar; 3 semester hours. Offered alternate years.
**Course Learning Outcomes**

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**GEOL611. SEQUENCE STRATIGRAPHY IN SEISMIC, WELL LOGS, AND OUTCROP. 3.0 Semester Hrs.**
Keynote lectures and a seminar series on the sequence stratigraphy of depositional systems, including both siliciclastics and carbonates and how they behave in changing sea-level, tectonic subsidence, and sediment supply conditions. Application of sequence stratigraphy concepts to reflection seismic, well-log, and outcrop datasets. Field trip and report required. Prerequisite: GEOL501. 3 hours lecture and seminar; 3 semester hours.
**Course Learning Outcomes**

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**GEOL613. GEOLOGIC RESERVOIR CHARACTERIZATION. 3.0 Semester Hrs.**
(I) Principles and practice of characterizing petro leum reservoirs using geologic and engineering data, including well logs, sample descriptions, routine and special core analysis and well tests. Emphasis is placed on practical analysis of such data sets from a variety of clastic petroleum reservoirs worldwide. These data sets are integrated into detailed characterizations, which then are used to solve practical oil and gas field problems. 3 hours lecture; 3 semester hours. Prerequisite: GEGN438, GEOL501, GEOL505 or equivalents.
**Course Learning Outcomes**

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**GEOL617. THERMODYNAMICS AND MINERAL PHASE EQUILIBRIA. 3.0 Semester Hrs.**
(I) Basic thermodynamics applied to natural geologic systems. Evaluation of mineral-vapor mineral solution, mineral-melt, and solid solution equilibria with special emphasis on oxide, sulfide, and silicate systems. Experimental and theoretical derivation, use, and application of phase diagrams relevant to natural rock systems. An emphasis will be placed on problem solving rather than basic theory. Prerequisite: DCGN209 or equivalent. 3 hours lecture; 3 semester hours. Offered alternate years.
**Course Learning Outcomes**

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**GEOL621. PETROLOGY OF DETRITAL ROCKS. 3.0 Semester Hrs.**
(II) Compositions and textures of sandstones, siltstones, and mudrocks. Relationship of compositions and textures of provenance, environment of deposition, and burial history. Development of porosity and permeability. Laboratory exercises emphasize use of petrographic thin sections, x-ray diffraction analysis, and scanning electron microscopy to examine detrital rocks. A term project is required, involving petrographic analysis of samples selected by student. Pre-requisites: GEGN206 , GEOL321 or equivalent. 2 hours lecture and seminar, 3 hours lab; 3 semester hours. Offered on demand.
**Course Learning Outcomes**

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**GEOL624. CARBONATE SEDIMENTOLOGY AND PETROLOGY. 3.0 Semester Hrs.**
(I) Processes involved in the deposition of carbonate sediments with an emphasis on Recent environments as analogs for ancient carbonate sequences. Carbonate facies recognition through bio- and lithofacies analysis, three-dimensional geometries, sedimentary dynamics, sedimentary structures, and facies associations. Laboratory stresses identification of Recent carbonate sediments and thin section analysis of carbonate classification, textures, non-skeletal and biogenic constituents, diagenesis, and porosity evolution. 2 hours lecture/seminar, 2 hours lab; 3 semester hours. Prerequisite: GEOL321 and GEOL314.
**Course Learning Outcomes**

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**GEOL628. ADVANCED IGNEOUS PETROLOGY. 3.0 Semester Hrs.**
(I) Igneous processes and concepts, emphasizing the genesis, evolution, and emplacement of tectonically and geochemically diverse volcanic and plutonic occurrences. Tectonic controls on igneous activity and petrochemistry. Petrographic study of igneous suites, mineralized and non-mineralized, from diverse tectonic settings. Prerequisites: GEOL321, GEGN206. 2 hours lecture, 3 hours lab; 3 semester hours. Offered alternate years.
**Course Learning Outcomes**

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**GEOL642. FIELD GEOLOGY. 1-3 Semester Hr.**
(S) Field program operated concurrently with GEGN316 field camp to familiarize the
student with basic field technique, geologic principles, and regional geology of Rocky Mountains. Prerequisite: Undergraduate degree in geology and GEGN316 or equivalent. During summer field session; 1 to 3 semester hours.
**Course Learning Outcomes**

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**GEOL643. GRADUATE FIELD SEMINARS. 1-3 Semester Hr.**
(I, II, S) Special advanced field programs emphasizing detailed study of some aspects of geology. Normally conducted away from the Golden campus. Prerequisite: Restricted to Ph.D. or advanced M.S. candidates. Usually taken after at least one year of graduate residence. Background requirements vary according to nature of field study. Fees are assessed for field and living expenses and transportation. 1 to 3 semester hours; may be repeated for credit.
**Course Learning Outcomes**

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**GEOL645. VOLCANOLOGY. 3.0 Semester Hrs.**
(I, II, S) Assigned readings and seminar discussions on volcanic processes and products. Principal topics include pyroclastic rocks, craters and calderas, caldron subsidence, diatremes, volcanic domes, origin and evolution of volcanic magmas, and relation of volcanism to alteration and mineralization. Petrographic study of selected suites of lava and pyroclastic rocks in the laboratory. 1 hour seminar, 6 hours lab; 3 semester hours. Prerequisite: none.
**Course Learning Outcomes**

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**GEOL653. CARBONATE DIAGENESIS AND GEOCHEMISTRY. 3.0 Semester Hrs.**
(II) Petrologic, geochemical, and isotopic approaches to the study of diagenetic changes in carbonate sediments and rocks. Topics covered include major near-surface diagenetic environments, subaerial exposure, dolomitization, burial diagenesis, carbonate aqueous equilibria, and the carbonate geochemistry of trace elements and stable isotopes. Laboratory stresses thin section recognition of diagenetic textures and fabrics, x-ray diffraction, and geochemical/isotopic approaches to diagenetic problems. Prerequisites: GEOL624. 2 hours lecture; 3 hours lab; 3 semester hours.
**Course Learning Outcomes**

- Recognize petrologic, geochemical, and isotopic approaches to the study of diagenetic changes in carbonate sediments and rocks.

**GEOL660. CARBONATE RESERVOIRS - EXPLORATION TO PRODUCTION ENGINEERING. 3.0 Semester Hrs.**
Equivalent with PEGN660,
(II) An introduction to the reservoir characterization of carbonate rocks, including geologic description, petrophysics, and production engineering. Develops an understanding of the integration of geology, rock physics, and engineering to improve reservoir performance. Application of reservoir concepts in hands-on exercises that include reflection seismic, well-log, and core data. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- See course objectives.

**GEOL698. SPECIAL TOPICS. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**GEOL699. INDEPENDENT STUDY IN GEOLOGY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**GEOL699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**GEOL699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**GEOL699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**GEOL699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**GEOL699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**GEOL699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**GEOL699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**GEOL707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.**
(I, II, S) Research credit hours required for completion of a Masters-level thesis or Doctoral dissertation. Research must be carried out under the direct supervision of the student's faculty advisor. Variable class and semester hours. Repeatable for credit.
**Course Learning Outcomes**

- .

**SYGN588. GIS-BASED REAL WORLD LEARNING PROJECT I - FUNDAMENTALS. 1-6 Semester Hr.**
This course requires a GIS-based project and report that demonstrate competence in the application of GIS to real word problems. The project topic and content of the report is determined by the course instructor, in consultation with the student. The format of the report will follow the guidelines for a professional journal paper. Variable credit: 1 to 6 credit hours. Repeatable for credit under different topics/experience and the cumulative maximum is 6 credit hours and 3 repeats total.

## Professor and Department Head

Alexis Navarre-Sitchler

## Professors

David A. Benson

Wendy A. Bohrson

Zhaoshan Chang, Charles F. Fogarty Endowed Chair

Thomas Monecke, Director of Center for Advanced Subsurface Earth Resource Models and Co-Director of Center for Mineral Resources Science

Alexis Navarre-Sitchler, Joint Faculty Appointee, Energy and Natural Resources Security Group Los Alamos National Laboratory

Piret Plink-Bjorklund

Eric Roberts, Director, Potential Gas Agency

Paul M. Santi, Director of the Institute for Initiatives in Latin America

Kamini Singha, Associate Dean of Earth and Society Programs

Stephen A. Sonnenberg, Charles Boettcher Distinguished Chair in Petroleum Geology

Lesli J. Wood, Robert Weimer Distinguished Chair

Wendy Zhou

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Mathias Burisch

Yvette Kuiper

Gabriel Walton

### Assistant Professors

Adrienne Marshall

Ryan Venturelli

### Research Professors

Marsha French

Richard Goldfarb

Zane Jobe, Director of the Chevron Center of Research Excellence

David Leach

J. Frederick Sarg

Richard Wanty

### Research Associate Professor

Katharina Pfaff

### Research Assistant Professors

Kevin Cannon

Mary Carr

Ben Frieman

Shiqiang Huang

Arnoud Slootman

### Teaching Professor

Christian V. Shorey

### Teaching Assistant Professor

Brendan Hanger

### Professor Emerita

Wendy Harrison

Eileen P. Poeter

### Professors Emeriti

John B. Curtis

Jerry D. Higgins

Murray W. Hitzman

Neil F. Hurley

Keenan Lee

Samuel B. Romberger

John E. Warme

Richard F. Wendlandt

### Associate Professors Emeriti

L. Graham Closs

Timothy A. Cross

Gregory S. Holden

Bruce Trudgill

# Geophysics

## Degrees Offered

- Graduate Certificate (Energy Geophysics)

- Master of Science (Geophysics) (Non-Thesis)
- Master of Science (Geophysical Engineering) (non-thesis)

- Master of Science (Geophysics)
- Master of Science (Geophysical Engineering)
- Doctor of Philosophy (Geophysics)
- Doctor of Philosophy (Geophysical Engineering)

## Program Description

Founded in 1926, the Department of Geophysics at Colorado School of Mines is recognized and respected around the world for its programs in applied geophysical research and education. Geophysics is a multidisciplinary field that blends geology, physics, mathematics, computer science, and electrical engineering. Professionals working in geophysics often come with training from programs in these allied disciplines, as well as from formal programs in geophysics.

Geophysicists study and explore the interior of the Earth (and other planetary bodies) through physical measurements collected at its surface and in the subsurface, as well as remotely via airborne and satellite platforms. Using a combination of mathematical analyses based on data collected using a multitude of sensitive sensors, and insight into physical and chemical processes cast in the relevant geological contexts, geophysicists reveal the detailed structure of the Earth’s interior and explain a multitude of societally relevant natural processes. Noninvasive imaging beneath the surface of geologic bodies by geophysicists is directly analogous to noninvasive imaging of the human body by medical specialists.

Earth supplies all the materials needed by our society, serves as the repository of used products, and provides a home to all its inhabitants. Geophysicists and geophysical engineers have important roles to play in solving challenging problems facing the inhabitants of the Earth, such as providing fresh water, food, and energy for its growing population, evaluating sites for underground construction and containment of hazardous waste, noninvasive monitoring of aging infrastructure (water and telecommunication conduits, transportation networks), mitigating the threat of geohazards to populated areas (earthquakes, volcanoes, landslides, avalanches), aid homeland security (through detection of underground activity and removal of unexploded ordnance or land mines), evaluating changes in climate and managing humankind’s response to them, as well as satisfying the human thirst for knowledge by exploring Earth and other planetary bodies.

Energy and mineral companies employ geophysicists to explore subsurface resources worldwide. Engineering firms hire geophysical engineers to assess Earth’s near-surface properties for large

construction and infrastructure projects. Environmental organizations rely on geophysics to conduct groundwater surveys and to track the flow, distribution, and concentration of contaminants. Geophysicists employed by universities and government agencies (e.g., U.S. Geological Survey or NASA), study dynamic Earth processes at all scales, from its deep interior to the oceans, ice sheets, and atmosphere.

With 12 full-time faculty members and small class sizes, Geophysics students receive individualized attention in a close-knit environment. Given the multidisciplinary nature of geophysics, the graduate curriculum equips students with a broad skillset, including applied mathematics and physics, geology, computing, and sensor engineering, in addition to theoretical and practical aspects of the geophysical field and laboratory methodologies.

Geophysicists are highly sought after, and for the past decade, 95% of Mines' geophysics graduates found employment in their chosen field within six months of graduation.

## Research Emphasis

The department conducts research in a wide variety of areas that are mostly related, but not restricted, to applied geophysics. Candidates interested in the current research activities of specific faculty members are encouraged to visit the department's webpage and to contact faculty members directly to gain insight into their scholarship. To give prospective candidates an idea of the types of research activities available in geophysics at Mines, a brief summary of research emphases and strengths in the department is given below.

**Discovering Earth and other planetary bodies.** Earth is a dynamic planet evolving over geologic and human time scales. Using geophysical data and methods, the department explores Earth from its surface to its core at all spatial and temporal scales. This broad perspective allows investigation of a wide range of topics including plate tectonics, natural hazards, mineral exploration, and ocean-atmosphere interactions. The department also uses geophysical and computational approaches to study other planet-like bodies to better understand the origin and evolution of the solar system and to explore space resources.

**Securing energy and mineral resources.** Affordable and abundant energy and minerals have facilitated and accelerated humankind's growth and development. Responding to energy balance changes due to technological advances and greater societal demands for sustainable resource use, the department's teaching and research adapts rapidly to maintain its integral role in innovation for effective and responsible access to Earth resources. The department is a leader in conventional and unconventional hydrocarbon resource evaluation, in exploration for essential critical minerals, as well as in underground carbon capture and storage. The department approaches these societal challenges through theoretical advancements, the development of multiphysics techniques, as well as state-of-the-art data analysis and high-performance computing.

**Sustaining communities and the environment.** Environmental assessment through geophysics is integral to humankind's interaction with the uppermost Earth crust, where humans live and develop thriving economies. The department excels at advancing near-surface geophysics through theoretical and technological advancements, development of low-cost instrumentation, working with communities to improve their understanding of environmental issues, and promoting society-informed science and communication. Active research in the department includes projects related to freshwater resources, subsurface contamination, climate dynamics, and sustainable energy and minerals exploration.

These research endeavors are supported through diverse funding sources including U.S. government agencies, international agencies/universities, and industry. Research funding supports multiple research groups within the department.

- **Center for Wave Phenomena (CWP)** focuses on seismic modeling, imaging, and inversion methods for realistic highly heterogeneous geologic structures through the development and application of high-performance computing and advancement of innovative technologies (e.g., robotics and distributed acoustic sensing [DAS]).
- **Reservoir Characterization Project (RCP)** utilizes a unique research model emphasizing multidisciplinary, collaborative research integrating multicomponent time-lapse 3D seismic reflection data, downhole data, reservoir geology and production data, distributed acoustic sensing (DAS), machine learning, and compressive sensing to solve complex reservoir challenges and optimize reservoir development on active industry projects.
- **Center for Gravity, Electrical and Magnetic Studies (CGEM)** brings together diverse expertise to quantitatively interpret and integrate gravity, magnetic, electrical and electromagnetic, as well as nuclear magnetic resonance data to advance geophysical data interpretation for real-world problems (e.g., mineral exploration, hydrogeophysics, geotechnical problems).
- **Center for Rock and Fluid Multiphysics (CRFM)** uses advanced laboratory experimental techniques and machine learning to study fluid distributions in rocks and how these distributions affect characteristics such as wave attenuation, velocity dispersion, and seismic signature.
- **Hydrogeology and Geomechanics Laboratory** integrates data from laboratory and field experiments at various scales to inform process-based models of near-surface problems including coastal freshwater, contaminant plumes, geothermal systems, landslides, leakage in earth dams and embankments, and volcanic processes.
- **Glaciology Laboratory** uses satellite remote-sensing techniques in combination with field-based and airborne geophysical methods to understand physical processes of Earth's glaciers and ice sheets and to overcome the inherent difficulty of observing continent-scale ice masses that drive and react to other components of the Earth's global climate system.
- **Geophysical Oceanography Group** combines high-resolution observations of winds, currents, and waves with theory and modeling to bridge the gap between the ocean and the atmosphere and further our understanding of how coupled air-sea interactions affect the environment including through wave dynamics and heat transfer.

## Program Requirements

The department offers both traditional, research-oriented graduate programs and a non-thesis professional education program designed to meet specific career objectives. The program of study is selected by the student, in consultation with an advisor, and with thesis committee approval, according to the student's career needs and interests. Specific degrees have specific requirements as detailed below.

## Geophysics and Geophysical Engineering Program Objectives

The principal objective for students pursuing the PhD degree in Geophysics or Geophysical Engineering is for Geophysics PhD graduates to be regarded by their employers as effective educators and/or innovative researchers in their early-career peer group. In support of this objective, the PhD programs in the Department of Geophysics are aimed at achieving these student outcomes:

- Graduates will command superior knowledge of Geophysics and fundamental related disciplines and a superior understanding of their importance in the social context.
- Graduates will independently be able to devise and independently conduct research leading to significant new knowledge and geophysical techniques.
- Graduates will be able to report their findings orally and in writing to a variety of specialist, generalist, and public audiences.

The chief objective for students pursuing the MS degree in Geophysics or Geophysical Engineering is for Geophysics MS graduates to be regarded by their employers as effective practitioners addressing earth, energy, and environmental problems with geophysical techniques. In support of this objective, the MS programs in the Department of Geophysics aim to achieve these student outcomes:

- Graduates will command superior knowledge of geophysics and fundamental related disciplines.
- Graduates will be able to conduct original research that results in new knowledge and geophysical techniques.
- Graduates will be able to report their findings orally and in writing.

## Master of Science Degrees (Non-Thesis): Geophysics and Geophysical Engineering

Students may obtain a Master of Science (MS) Degree (non-thesis) in either Geophysics or Geophysical Engineering, pursuant to the general and individual program requirements outlined below. Students typically complete this program in one to two years.

For either Master of Science (non-thesis) degree, the minimum credits required include:

| | | |
|---|---|---|
| LICM501 or SYGN683 | PROFESSIONAL ORAL COMMUNICATION ORAL COMMUNICATION SKILLS | 1.0 |
| GPGN581 | GRADUATE SEMINAR | 1.0 |
| GPGN583 | READING SEMINAR | 1.0 |
| | THEORY COURSEWORK [1] | 3.0 |
| | APPLICATION COURSEWORK [1] | 3.0 |
| | COMPUTATIONAL COURSEWORK [1] | 3.0 |
| | EARTH & SPACE COURSEWORK [1] | 3.0 |
| | ADDITIONAL COURSEWORK | 15.0 |
| **Total Semester Hrs** | | **30.0** |

[1] The lists of pre-approved elective courses satisfying the Theory, Application, Computational and Earth & Space coursework requirements may be found below.

The student and advisor determine individual courses constituting the degree to address specific interests and career goals. The courses applied to all MS degrees must satisfy the following specific criteria:

- The 30-credit hour minimum total must include 15 credit hours of GPGN-listed courses.
- A maximum of 6 credit hours of independent study may be counted toward the degree program.
- All course, transfer, residence, and thesis requirements are as described in Registration and Tuition Classification and Graduate Degrees and Requirements sections of the catalog.
- Up to 6 credits of graduate level work may be double counted in the undergraduate and graduate degree for students enrolled in the Combined Degree.
- Additional courses may also be required by the student's advisor and committee to fulfill background requirements.

The coursework for the degree Master of Science, Geophysical Engineering, must meet the following specific requirements. Note that these requirements are in addition to those associated with the Master of Science in Geophysics.

- Students must complete, either prior to their arrival at Mines or while at Mines, no fewer than 16 credits of engineering coursework. What constitutes coursework considered as engineering is determined by the Geophysics faculty.

### Computational Geophysics Track

The Computational Geophysics Track has the same requirements as the Geophysics Master's of Science (non-thesis) degree program described above except that students are expected to choose coursework that satisfies a minimum of 15 credit hours, of which a minimum of 6 credits hours must be GPGN listed from the list of pre-approved computational coursework electives may be found below.

## Master of Science Degrees: Geophysics and Geophysical Engineering

Students may obtain a Master of Science (MS) Degree in either Geophysics or Geophysical Engineering, pursuant to the general and individual program requirements outlined below. Students typically complete this program in two years.

For either Master of Science degree, the minimum credits required include:

| | | |
|---|---|---|
| LICM501 or SYGN683 | PROFESSIONAL ORAL COMMUNICATION ORAL COMMUNICATION SKILLS | 1.0 |
| GPGN581 | GRADUATE SEMINAR | 1.0 |
| GPGN583 | READING SEMINAR | 1.0 |
| | THEORY COURSEWORK [1] | 3.0 |
| | COMPUTATIONAL COURSEWORK [1] | 3.0 |
| | APPLICATION COURSEWORK [1] | 3.0 |
| | EARTH & SPACE COURSEWORK [1] | 3.0 |
| | ADDITIONAL COURSEWORK [2] | 9.0 |
| GPGN707 | GRADUATE THESIS / DISSERTATION RESEARCH CREDIT | 6.0 |
| **Total Semester Hrs** | | **30.0** |

[1]The lists of pre-approved elective courses satisfying the Theory, Application, Computational and Earth & Space coursework requirements may be found below.

[2]With the approval of the student's thesis committee, up to 4 additional GPGN707 research credits beyond the 6 GPGN707 credits required

for the degree program can counted toward satisfying the additional coursework requirement.

The student and advisor, with approval from the thesis committee, determines individual courses constituting the degree to address specific interests and career goals. The courses applied to all MS degrees must satisfy the following specific criteria:

- The 30-credit hour minimum total must include 15 credit hours of GPGN-listed courses.
- A maximum of 6 credit hours of independent study may be counted toward the degree program.
- All course, research, transfer, residence, and thesis requirements are as described in Registration and Tuition Classification and Graduate Degrees and Requirements sections of the catalog.
- Up to 6 credits of graduate level work may be double counted in the undergraduate and graduate degree for students enrolled in the Combined Degree.
- Additional courses may also be required by the student's advisor and committee to fulfill background requirements.

The coursework and thesis topic for the degree Master of Science, Geophysical Engineering, must meet the following specific requirements. Note that these requirements are in addition to those associated with the Master of Science in Geophysics.

- Students must complete, either prior to their arrival at Mines or while at Mines, no fewer than 16 credits of engineering coursework. What constitutes coursework considered as engineering is determined by the Geophysics faculty.
- The student’s dissertation topic must be appropriate for inclusion as part of an Engineering degree, as determined by the Geophysics faculty.

As described in the Master of Science, Thesis and Thesis Defense section of this catalog, all MS candidates must successfully defend their MS thesis in a public oral thesis defense. The guidelines for the thesis defense enforced by the Department of Geophysics generally follow those outlined in in the Graduate Departments and Programs section of the catalog, with one exception. The Department of Geophysics requires students submit the final draft of their written thesis to their thesis committee a minimum of three weeks prior to the thesis defense date.

## Mines' Combined Undergraduate/Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate level coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

# Doctor of Philosophy Degrees: Geophysics and Geophysical Engineering

We invite applications to our Doctor of Philosophy (PhD) program not only from those individuals with a background in geophysics, but also from those whose background is in allied disciplines such as geology, physics, mathematics, computer science, or electrical engineering. Our program is suitable for students who desire careers in research-intensive environments, including government agencies and academia. Students typically complete the PhD program in four to five years.

Students may obtain a PhD degree in either Geophysics or Geophysical Engineering, pursuant to the general and individual program requirements outlined below.

For either PhD degree, at least 72 credits beyond the bachelor's degree are required. Of that total, at least 24 research credits are required. At least 12 course credits must be completed in a minor program of study, approved by the candidate's PhD thesis committee. Up to 36 course credits may be awarded by the candidate's committee for completion of a thesis-based master's degree. Graduate-level coursework completed as part of a thesis-based master’s degree with a focus on the Theory, Application, Computational, Earth & Space or Professional Development coursework may be used to satisfy the related theme with approval of the candidate’s committee.

While individual courses constituting the degree are determined by the student and approved by the student's advisor and committee, courses applied to all PhD degrees must satisfy the following criteria:

- The 72-credit hour minimum total must include 36 credit hours of GPGN-listed courses.
- A maximum of 6 credit hours of independent study may be counted toward the degree program.
- All course, research, minor degree programs, transfer, residence, and thesis requirements are as described in Registration and Tuition Classification and Graduate Degrees and Requirements sections of the catalog.
- Students must include the following courses in their PhD program:

| | | |
|---|---|---|
| | THEORY COURSEWORK [1] | 3.0 |
| | APPLICATION COURSEWORK [1] | 3.0 |
| | COMPUTATIONAL COURSEWORK [1] | 3.0 |
| | EARTH & SPACE COURSEWORK [1] | 3.0 |
| | PROFESSIONAL DEVELOPMENT COURSEWORK [1] | 3.0 |
| | ADDITIONAL COURSEWORK [2] | 20.0 |
| | COMPLEMENTARY COURSEWORK [3] | 12.0 |
| LICM501 or SYGN683 | PROFESSIONAL ORAL COMMUNICATION [4] ORAL COMMUNICATION SKILLS | 1.0 |
| GPGN707 | GRADUATE THESIS / DISSERTATION RESEARCH CREDIT | 24.0 |
| **Total Semester Hrs** | | **72.0** |

[1] The lists of pre-approved elective courses satisfying the Theory, Application, Computational, Earth & Space, and Professional Development coursework requirements may be found below.

[2] With approval of the student's thesis committee, additional GPGN707 research credits beyond the 24 GPGN707 required for the degree program can counted toward satisfying the additional coursework requirement.

[3] The complementary coursework requirement may be satisfied by minor, graduate certificate, or set of courses that provide the spirit of minor or graduate certificate, as approved by the PhD committee,

the geophysics graduate advisory committee, and the Geophysics Department.

(4) Can be replaced by 1 credit from the pre-approved professional development coursework list if already taken as part of a previous graduate degree program.

Additional courses may also be required by the student's advisor and committee to fulfill background requirements described below. The coursework and thesis topic for the degree Doctor of Philosophy, Geophysical Engineering, must meet the following additional requirements:

- Students must complete, either prior to their arrival at Mines or while at Mines, no fewer than 16 credits of engineering coursework. What constitutes coursework considered as engineering is determined by the Geophysics faculty.
- The student's dissertation topic must be appropriate for inclusion as part of an Engineering degree, as determined by the Geophysics faculty.

Students in both PhD programs are also required to participate in a practical teaching experience. This requirement must be fulfilled, within a single semester and course, under observation and evaluation by the course instructor of record, and include:

- Planning and delivery of a minimum of 6 lecture hours, or 4 lecture hours and 2 labs.
- Creating and evaluating students' homework and laboratory reports, if appropriate.
- Holding office hours if necessary.

In both PhD programs, students must demonstrate the potential for successful completion of independent research and enhance the breadth of their expertise by completing a Doctoral Research qualifying exam not later than two years from the date of enrollment in the program. An extension of one additional year may be petitioned by students through their thesis committees. In the Department of Geophysics, the Doctoral Research qualifying exam consists of the preparation, presentation, and defense of one research project and a thesis proposal. The research project and thesis proposal used in this process must conform to the standards posted on the Department of Geophysics webpage. As described in the Doctor of Philosophy Thesis Defense section of this catalog, all PhD candidates must successfully defend their PhD thesis in an open oral thesis defense. The guidelines for the thesis defense enforced by the Department of Geophysics follow those outlined in the Graduate Departments and Programs section of the catalog, with one exception. The Department of Geophysics requires students submit the final draft of their written thesis to their thesis committee a minimum of three weeks prior to the thesis defense date.

### Acceptable Thesis Formats

In addition to traditional dissertations, the Department of Geophysics also accepts dissertations that are compendia of papers published or submitted to peer-reviewed journals. Dissertations submitted in the latter format must adhere to the following guidelines.

- All papers included in the dissertation must have a common theme, as approved by a student's thesis committee.
- Papers should be submitted for inclusion in a dissertation in a uniform format and typeset.
- In addition to the individual papers, students must prepare abstract, introduction, discussion, and conclusions sections of the thesis that tie together the individual papers into a unified dissertation.
- A student's thesis committee might also require the preparation and inclusion of various appendices with the dissertation in support of the papers prepared explicitly for publication.

## Graduate Program Background Requirements

All graduate programs in Geophysics require that applicants have a background that includes the equivalent of adequate undergraduate preparation in the following areas:

- Mathematics – Linear Algebra or Linear Systems, Differential Equations, and Computer Programming
- Physics – Classical Mechanics, and Electromagnetism
- Geology – Structural Geology and Stratigraphy
- Geophysics – Courses that include theory and application in three of the following areas: gravity/magnetics, seismology, electrical/electromagnetics, borehole geophysics, remote sensing, geodynamics, oceanography and fluid dynamics.
- Field and computational experience in the hands-on application or implementation of several geophysical methods.

**NOTES:**

**Theory, Application, Computational, Earth & Space, and Professional Development Coursework Definitions**

- **Theory Coursework (pre-approved 500/600 level course electives)**
  a. Provides graduate-level foundation in geophysical theory while allowing flexibility based on interest and/or need.
  b. Key Learning Outcome: Use first principles of mathematics and physics to derive models that explain fundamental processes of the Earth and other planetary bodies.

| | | |
|---|---|---|
| GPGN510 | MACHINE LEARNING INVERSION IN APPLIED GEOSCIENCE | 3.0 |
| GPGN511 | ADVANCED GRAVITY AND MAGNETIC METHODS | 3.0 |
| GPGN520 | ELECTRICAL AND ELECTROMAGNETIC EXPLORATION | 3.0 |
| GPGN552 | INTRODUCTION TO SEISMOLOGY I | 3.0 |
| GPGN553 | INTRODUCTION TO SEISMOLOGY II | 3.0 |
| GPGN555 | EARTHQUAKE SEISMOLOGY | 3.0 |
| GPGN651 | ADVANCED SEISMOLOGY | 3.0 |
| GPGN658 | SEISMIC WAVEFIELD IMAGING | 3.0 |

- **Application Coursework (pre-approved 500/600 level course electives)**

  1. Provides graduate-level foundation in applied geophysics while allowing flexibility based on interest and/or need.
  2. Key Learning Outcome: Ability to design and execute experiments to collect, process, and interpret data in order to gain knowledge about the Earth and other planetary bodies.

| | | |
|---|---|---|
| GPGN503 | INTEGRATED EXPLORATION AND DEVELOPMENT | 3.0 |

| | | |
|---|---|---|
| GPGN545 | INTRODUCTION TO DISTRIBUTED FIBER-OPTIC SENSING AND ITS APPLICATIONS | 3.0 |
| GPGN547 | PHYSICS, MECHANICS, AND PETROPHYSICS OF ROCKS | 3.0 |
| GPGN558 | SEISMIC DATA INTERPRETATION AND QUANTITATIVE ANALYSIS | 3.0 |
| GPGN561 | SEISMIC DATA PROCESSING I | 4.0 |
| GPGN570 | APPLICATIONS OF SATELLITE REMOTE SENSING | 3.0 |
| GPGN574 | ADVANCED HYDROGEOPHYSICS | 3.0 |
| GPGN577 | HUMANITARIAN GEOSCIENCE | 3.0 |
| GPGN590 | INSTRUMENTAL DESIGN IN APPLIED GEOSCIENCES | 3.0 |
| CCUS521 | GEOLOGICAL CARBON CAPTURE UTILIZATION AND SEQUESTRATION (CCUS) | 3.0 |

- **Computational Coursework (pre-approved 500/600 level course electives)**
  a. Provides graduate-level foundation in computational geophysics while allowing flexibility based on interest and/or need.
  b. Key Learning Outcome: Familiarization with numerical implementation of geophysical theory and modern computational techniques, such as data science, machine learning, algorithm development, cluster computing, and parallel processing.

| | | |
|---|---|---|
| GPGN536 | ADVANCED GEOPHYSICAL COMPUTING I | 3.0 |
| GPGN537 | ADVANCED GEOPHYSICAL COMPUTING II | 3.0 |
| GEOL558 | EARTH RESOURCE DATA SCIENCE 2: APPLICATIONS AND MACHINE-LEARNING | 3.0 |
| MATH540 | PARALLEL SCIENTIFIC COMPUTING | 3.0 |
| MATH550 | NUMERICAL SOLUTION OF PARTIAL DIFFERENTIAL EQUATIONS | 3.0 |
| MATH551 | COMPUTATIONAL LINEAR ALGEBRA | 3.0 |
| CSCI542 | SIMULATION | 3.0 |
| CSCI563 | PARALLEL COMPUTING FOR SCIENTISTS AND ENGINEERS | 3.0 |
| CSCI568 | DATA MINING | 3.0 |
| CSCI580 | ADVANCED HIGH PERFORMANCE COMPUTING | 3.0 |
| EENG509 | SPARSE SIGNAL PROCESSING | 3.0 |
| EENG511 | CONVEX OPTIMIZATION AND ITS ENGINEERING APPLICATIONS | 3.0 |
| EENG515 | MATHEMATICAL METHODS FOR SIGNALS AND SYSTEMS | 3.0 |
| DSCI560 | INTRODUCTION TO KEY STATISTICAL LEARNING METHODS I | 3.0 |
| DSCI561 | INTRODUCTION TO KEY STATISTICAL LEARNING METHODS II | 3.0 |
| DSCI575 | ADVANCED MACHINE LEARNING | 3.0 |

- **Earth & Space Coursework (pre-approved 500/600 level course electives)**
  a. Provides graduate-level foundation in conceptual modeling of the Earth while allowing flexibility based on interest and/or need.
  b. Key Learning Outcome: Development of conceptual models to explain the observed natural complexity of earth materials and processes.

| | | |
|---|---|---|
| CCUS520 | CLIMATE CHANGE AND SUSTAINABILITY | 3.0 |
| CHGC503 | INTRODUCTION TO GEOCHEMISTRY | 3.0 |
| CHGC505 | INTRODUCTION TO ENVIRONMENTAL CHEMISTRY | 3.0 |
| GEOL501 | APPLIED STRATIGRAPHY | 4.0 |
| GEOL502 | STRUCTURAL METHODS FOR SEISMIC INTERPRETATION | 3.0 |
| GEOL505 | ADVANCED STRUCTURAL GEOLOGY | 3.0 |
| GEOL513 | HYDROTHERMAL GEOCHEMISTRY | 3.0 |
| GEOL552 | UNCONVENTIONAL PETROLEUM SYSTEMS | 3.0 |
| GEOL551 | APPLIED PETROLEUM GEOLOGY | 3.0 |
| GEOL645 | VOLCANOLOGY | 3.0 |
| GEGN508 | ADVANCED ROCK MECHANICS | 3.0 |
| GEGN570 | CASE HISTORIES IN GEOLOGICAL ENGINEERING AND HYDROGEOLOGY | 3.0 |
| GEGN582 | INTEGRATED SURFACE WATER HYDROLOGY | 3.0 |
| GEGN583 | MATHEMATICAL MODELING OF GROUNDWATER SYSTEMS | 3.0 |
| GEGN671 | LANDSLIDES: INVESTIGATION, ANALYSIS & MITIGATION | 3.0 |
| SYGN598 | INTRODUCTION TO GEOTHERMAL RESOURCES | |

- **Professional Development Coursework (pre-approved 500/600 level course electives)**

  1. Provides opportunities for professional development while allowing flexibility based on interest and/or need.
  2. Key Learning Outcome: Development of a superior understanding of the importance of geophysics and fundamental related disciplines within the social context.

| | | |
|---|---|---|
| SYGN501 | RESEARCH SKILLS FOR GRADUATE STUDENTS | 1.0 |
| SYGN502 | INTRODUCTION TO RESEARCH ETHICS | 1.0 |
| GPGN581 | GRADUATE SEMINAR | 1.0 |
| EBGN510 | NATURAL RESOURCE ECONOMICS | 3.0 |
| EBGN542 | ECONOMIC DEVELOPMENT | 3.0 |
| EBGN553 | PROJECT MANAGEMENT | 3.0 |
| EBGN563 | MANAGEMENT OF TECHNOLOGY AND INNOVATION | 3.0 |
| EDNS515 | INTRODUCTION TO SCIENCE AND TECHNOLOGY STUDIES | 3.0 |
| EDNS544 | INNOV8X | 3.0 |

## Program Requirements

## Graduate Certificate in Energy Geophysics

The Graduate Certificate in Energy Geophysics will be a fully online certificate. The applicant is required to have an undergraduate degree to be admitted into the program. Students working toward their graduate certificate are required to take 12 credits from the following list of approved courses:

| | | |
|---|---|---|
| GPGN519 | ADVANCED FORMATION EVALUATION | 3.0 |
| GPGN545 | INTRODUCTION TO DISTRIBUTED FIBER-OPTIC SENSING AND ITS APPLICATIONS | 3.0 |
| GPGN547 | PHYSICS, MECHANICS, AND PETROPHYSICS OF ROCKS | 3.0 |
| GPGN558 | SEISMIC DATA INTERPRETATION AND QUANTITATIVE ANALYSIS | 3.0 |
| GPGN651 | ADVANCED SEISMOLOGY | 3.0 |
| CCUS521 | GEOLOGICAL CARBON CAPTURE UTILIZATION AND SEQUESTRATION (CCUS) | 3.0 |
| SYGN598 | INTRODUCTION TO GEOTHERMAL RESOURCES | 3.0 |

Students must achieve a minimum average grade of B (3.0) for the four required courses.

## Courses

**GPGN503. INTEGRATED EXPLORATION AND DEVELOPMENT. 3.0 Semester Hrs.**
(I) Students work alone and in teams to study reservoirs from fluvial-deltaic and valley fill depositional environments. This is a multidisciplinary course that shows students how to characterize and model subsurface reservoir performance by integrating data, methods and concepts from geology, geophysics and petroleum engineering. Activities include field trips, computer modeling, written exercises and oral team presentations. Prerequisite: none. 2 hours lecture, 3 hours lab; 3 semester hours. Offered fall semester, odd years.

**GPGN509. INVERSION. 3.0 Semester Hrs.**
This course introduces the fundamentals of inverse problem theory as applied to geophysics. Students explore the fundamental concepts of inversion in probabilistic and deterministic frameworks, as well as practical methods for solving discrete inverse problems. Topics studied include optimization criteria, optimization methods, and error and resolution analysis. Weekly homework assignments addressing either theoretical or numerical problems through programming assignments illustrate the concepts discussed in class. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Students will understand the fundamental principles of probabilistic and deterministic inversion.
- Students will understand the main methods used to quantify measurement uncertainty.
- Students will understand the relationships between probabilistic and deterministic solutions to inverse problems.
- Students will understand the basic techniques for obtaining numeric solutions to inverse problems.

**GPGN510. MACHINE LEARNING INVERSION IN APPLIED GEOSCIENCE. 3.0 Semester Hrs.**
This course presents the fundamentals of formulating and solving inverse problems when the models to be recovered are functions in applied geosciences. The emphases are on the basic strategies for solving linear and nonlinear inverse problems and on the practical methodologies for constructing models that can be directly used in subsequent simulations and interpretations. The course will cover model construction and uncertainty quantification using Tikhonov regularization, machine learning (ML), and generative artificial intelligence. The course will and integration of information the data to be inverted and the information in the complementary data that are conceptual in nature.
**Course Learning Outcomes**

- Understanding and skills in the classical regularized inversion for model construction and appraisal
- Understanding and skills in the emerging machine learning and artificial intelligence inversions and uncertainty quantification.
- Understanding in information transfer and extraction through inversion for decision-making in applied geosciences

**GPGN511. ADVANCED GRAVITY AND MAGNETIC METHODS. 3.0 Semester Hrs.**
This course presents the theory and methods for processing and interpreting gravity and magnetic data acquired in geoscience applications. The course covers four major topic areas in the gravity and magnetic methods: (1) the data quantities measured in field surveys; (2) the methods for modeling, processing, and analyzing gravity, gravity gradient, and magnetic data; (3) 3D inversion of gravity and magnetic data; and (4) integrated interpretation of gravity and magnetic data through inversion and geology differentiation for extracting geology information. Prerequisites: GPGN314, GPGN328.
**Course Learning Outcomes**

- Graduates will demonstrate exemplary disciplinary expertise.

**GPGN519. ADVANCED FORMATION EVALUATION. 3.0 Semester Hrs.**
A detailed review of well logging and other formation evaluation methods will be presented. Course includes an overview of the logging environment, how different basic and advanced logging tools work, how logging measurements are converted to geophysical properties, how geophysical properties relate to physical and chemical properties of fluids and rocks, and how log data are tied with seismic data.

**GPGN520. ELECTRICAL AND ELECTROMAGNETIC EXPLORATION. 3.0 Semester Hrs.**
(II) Electromagnetic theory. Instrumentation. Survey planning. Processing of data. Geologic interpretations. Methods and limitations of interpretation. Offered Spring semester in conjunction with GPGN420. Prerequisite: GPGN314. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- NA

**GPGN530. APPLIED GEOPHYSICS. 3.0 Semester Hrs.**
(II) Introduction to geophysical techniques used in a variety of industries (mining, petroleum, environmental and engineering) in exploring for new deposits, site design, etc. The methods studied include gravity, magnetic, electrical, seismic, radiometric and borehole techniques. Emphasis on techniques and their applications are tailored to student interests. The course, intended for non-geophysics students, will emphasize the theoretical basis for each technique, the instrumentation used and data collection, processing and interpretation procedures specific to each technique so that non-specialists can more effectively evaluate the results of geophysical investigations. 3 hours lecture; 3 semester hours.

**GPGN533. GEOPHYSICAL DATA INTEGRATION & GEOSTATISTICS. 3.0 Semester Hrs.**
(I) Students will learn the fundamentals of and explore opportunities for further development of geostatistical data integration techniques for subsurface earth modeling. The class will build on probability theory, spatial correlations and geostatistics algorithms for combing data of diverse support and resolution into subsurface models. The emphasis of the material will be on stochastic methods for combining quantitative and qualitative data into many equi-probable realizations. Activities

include computer modeling, written exercises, oral team presentations, and a semester project with opportunity to enhance student's respective research projects. Also, we will read, discuss and implement current research articles the in literature to encourage implementation of state-of-the-art practices and/or highlighting current opportunities for research. 3 hours lecture; 3 semester hours.

**GPGN536. ADVANCED GEOPHYSICAL COMPUTING I. 3.0 Semester Hrs.**
This course extends the principles of geophysical computing in the context of simulating and validating numerical solutions to geophysical data processing challenges and 2D/3D partial differential equations commonly found in geophysical investigations. Students develop 2D and 3D numerical solutions to geophysical problems through prototyping and validating code in both high- (e.g., Python) and low-level (e.g., C/C++/F90) languages. Offered in conjunction with GPGN435. Prerequisite: CSCI250 or instructor consent.
**Course Learning Outcomes**

- Students will gain experience in taking theoretical concepts and using them to develop, prototype and validate parallel numerical algorithms in the context of geophysical computing.
- Students will gain mastery of practical programming skills and combine with knowledge of numerical algorithms to solve real-world geophysical problems.
- Students will augment their independent research skills by devising and leading a research project involving a substantial piece of analytic, numerical and computation work involving solving a real-world geophysical problem

**GPGN537. ADVANCED GEOPHYSICAL COMPUTING II. 3.0 Semester Hrs.**
A survey of computer programming skills most relevant to geophysical modeling, data processing, visualization, and analysis. Skills enhanced include effective use of multiple programming languages, multicore systems, computer memory hierarchies, GPUs, and parallel computing strategies. Problems addressed include multidimensional geophysical partial differential equations, geophysical image processing, regularization of geophysical data acquired at scattered locations, and other geophysical computing problems encountered in research by students. Prerequisite: GPGN536 or instructor consent.
**Course Learning Outcomes**

- Students will gain mastery in taking theoretical concepts and using them to develop, prototype and validate parallel numerical algorithms in the context of geophysical computing.
- Students will gain mastery of practical programming skills and combine with knowledge of numerical algorithms to solve real-world geophysical problems.
- Students will augment their independent research skills by devising and leading a project involving a substantial piece of analytic, numerical and computation work involving solving a real-world geophysical problem.

**GPGN543. MINERAL EXPLORATION GEOPHYSICS. 3.0 Semester Hrs.**
This course focuses on geophysical methods in mineral exploration by integrating mineral deposit theory and commonly employed geophysical methods. We begin with a background discussion on the geological setting and physical property characteristics of major deposit types to lay the foundational understanding for different geophysical method. We will then discuss the physical principles and operations of different geophysical methods, and the interpretation of geophysical data sets to extract geological information through geophysical inversion. We will then discuss the emerging methods for efficient data acquisition, and integrated exploration methodology of geology differentiation that combines the geologic, physical property, and geophysical information to produce a quasi-geology model to image the geology.
**Course Learning Outcomes**

- Explain the connection between geophysical and economic geology
- Discuss the physical basis for different geophysical methods
- Evaluate the information in geophysical data and inverted physical property models
- Devise a geophysical exploration strategy for a mineral exploration program

**GPGN545. INTRODUCTION TO DISTRIBUTED FIBER-OPTIC SENSING AND ITS APPLICATIONS. 3.0 Semester Hrs.**
This course will first introduce the fundamentals of Distributed Fiber-optic Sensing (DFOS) technologies, including the measuring principles, calibration process, advantages, and limitations. Then we will explore the recent development of DFOS applications in geophysics, petroleum engineer, smart city, hydrology, and other fields. Three major technologies of DFOS will be introduced: distributed acoustic sensing (DAS), distributed temperature sensing (DTS), and distributed strain sensing (DSS). Prerequisite: Python programming, signal processing.
**Course Learning Outcomes**

- 1. Students will learn the principle, advantages, and limitations of DFOS systems.
- 2. Students will learn recent DFOS application developments.
- 3. Students will be able to apply the theories to realistic DFOS applications.
- 4. Students will be able to learn how to handle, process, visualize DFOS data using Python programming and Google Colab.
- 5. Students will be able to perform DFOS data analysis to obtain the required results.

**GPGN547. PHYSICS, MECHANICS, AND PETROPHYSICS OF ROCKS. 3.0 Semester Hrs.**
This course will discuss topics in rock physics, rock mechanics and petrophysics as outlined below. The class is a combination of lectures, practical sessions, and critical reading and discussion of papers. Topics addressed: Segment in Rock physics: stress, strain, stiffness, modulus, attenuation and dispersion, Segment in Petrophysics: seismic & log expression of various formations, wettability, shale analysis, diagenesis, formation evaluation.
**Course Learning Outcomes**

- First-order Level Learning Objectives • Gain an introduction to and a working knowledge of the main topics in rock physics • Understand and evaluate technical topics related to rock physics applications • Have insight into basic techniques to evaluate reservoirs • Learn tools to assess reserves, and learn best techniques to use rock physics principles
- Second-order Learning Objectives • identify major & minor rock-forming minerals • evaluate or recall elastic properties of major rock-forming minerals • classify mineral components as load-bearing or pore-filling • compute modulus of a dry rock frame constructed with major minerals • know isotropic and other (major) symmetries • predict modulus changes in fluid and frame with stress • predict modulus changes with cementation • evaluate / defend role of

porosity, cementation and diagenesis on elastic properties • evaluate and appraise elastic modulus of frame with geological and well log information • explain differences between static and dynamic stresses, strains and moduli • classify lithological texture to expected acoustic anisotropy • compute elastic bounds: Voigt, Reuss, Hashin-Shtrikman, modified H-S • compute Empirical velocity models

**GPGN552. INTRODUCTION TO SEISMOLOGY I. 3.0 Semester Hrs.**
(I) Introduction to basic principles of elasticity including Hooke's law, equation of motion, representation theorems, and reciprocity. Representation of seismic sources, seismic moment tensor, radiation from point sources in homogeneous isotropic media. Boundary conditions, reflection/transmission coefficients of plane waves, plane-wave propagation in stratified media. Basics of wave propagation in attenuative media, brief description of seismic modeling methods. 3 hours lecture; 3 semester hours.

**GPGN553. INTRODUCTION TO SEISMOLOGY II. 3.0 Semester Hrs.**
(II) This course is focused on the physics of wave phenomena and the importance of wave-theory results in exploration and earthquake seismology. Includes reflection and transmission problems for spherical waves, methods of steepest descent and stationary phase, point-source radiation in layered isotropic media, surface and non-geometrical waves. Discussion of seismic modeling methods, fundamentals of wave propagation in anisotropic and attenuative media. Prerequisite: GPGN552. 3 hours lecture; 3 semester hours. Offered spring semester, even years.

**GPGN555. EARTHQUAKE SEISMOLOGY. 3.0 Semester Hrs.**
Equivalent with GPGN455,
(I) Earthquakes are amongst the most significant natural hazards faced by mankind, with millions of fatalities forecast this century. They are also our most accessible source of information on Earth's structure, rheology and tectonics, which are what ultimately govern the distribution of its natural resources. This course provides an overview of how earthquake seismology, complemented by geodesy and tectonic geomorphology, can be used to determine Earth structure, earthquake locations, depths and mechanisms; understand Earth's tectonics and rheology; establish long-term earthquake histories and forecast future recurrence; and mitigate against seismic hazards. GPGN555 differs from GPGN455 in that the assignments are approximately 20% longer and encompass more challenging questions. GPGN555 is the appropriate course for graduate students and for undergraduates who expect to go on to study earthquake seismology at graduate school. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- 3a, b, d, f, g, h, j, k

**GPGN558. SEISMIC DATA INTERPRETATION AND QUANTITATIVE ANALYSIS. 0-3 Semester Hr.**
This course gives participants an understanding of how to model, understand, interpret and analyze seismic data in a quantitative manner on several worldwide projects. When you look at seismic data, how does it relate to the rock properties, what do the amplitudes mean, what is tuning, what is a wavelet, how does the seismic relate to structure, and what are seismic attributes and inversion products? How do you use this information in exploration, production and basic volumetric and economics calculations? The course will go over these topics. Students will work in teams on several modeling and seismic field data exercises around the world in most widely used software platforms (Ikon-RokDoc, Schlumberger-Petrel, GEOX, CGG-HampsonRussell). The course aims to give participants knowledge and information to assist in professional and career development and to be operationally prepared for the work environment. Prerequisites: GPGN461 or GPGN 561 and GEOL309 or GEOL314.
**Course Learning Outcomes**

- NA

**GPGN561. SEISMIC DATA PROCESSING I. 4.0 Semester Hrs.**
This course covers the basic processing steps required to create images of the earth using 2D and 3D reflection seismic data. Topics include data organization and domains, signal processing to enhance temporal and spatial resolution, identification and suppression of incoherent and coherent noise, velocity analysis, near-surface statics, datuming, normal- and dip-moveout corrections, common-midpoint stacking, principles and methods used for poststack and prestack time and depth imaging, post-imaging enhancement techniques. Field data are extensively used throughout the course. A three-hour lab introduces the student to hands-on data processing using a Seismic Unix software package. The final project consists of processing a 2D seismic line with oral presentation of the results.
**Course Learning Outcomes**

- NA

**GPGN570. APPLICATIONS OF SATELLITE REMOTE SENSING. 3.0 Semester Hrs.**
(II) An introduction to geoscience applications of satellite remote sensing of the Earth and planets. The lectures provide background on satellites, sensors, methodology, and diverse applications. Topics include visible, near infrared, and thermal infrared passive sensing, active microwave and radio sensing, and geodetic remote sensing. Lectures and labs involve use of data from a variety of instruments, as several applications to problems in the Earth and planetary sciences are presented. Students will complete independent term projects that are presented both written and orally at the end of the term. Prerequisites: PHGN200 and MATH225. 2 hours lecture, 2 hours lab; 3 semester hours.

**GPGN573. POLAR CRYOSPHERE IN THE EARTH SYSTEM. 3.0 Semester Hrs.**
The polar cryosphere is a fundamental and rapidly changing component of the physical Earth system as well as of other planetary bodies that both drives and responds to climate perturbations. This course will provide an introduction to the interdisciplinary nature of permafrost, sea ice, glaciers, and ice sheets, then dive deeper into the fundamental physics of glacier and ice-sheet dynamics and their application to global sea level, paleoclimate, and planetary science questions. We will cover topics including glacier mass balance, ice material properties, ice rheology, models of ice #ow, supra-, en-, and subglacial hydrology, subglacial geologic processes, and the stability and history of Earth's ice sheets. Although aimed at a broad audience interested in climate, geophysics, and planetary science, students will be expected to have a background understanding of undergraduate-level mathematics through differential equations and basic Python programming experience. Succeeding in this class is certainly possible without formal coursework in differential equations and programming, but may require additional out-of-class self-study to learn these skills in real time. Prerequisite: CSCI 128 or similar; MATH 225 or similar.
**Course Learning Outcomes**

- 1. Demonstrate a conceptual understanding of feedbacks between the polar cryosphere and the Earth's climate system
- 2. Critically analyze peer-reviewed literature in polar cryosphere

- 3. Understand the equations that govern glacier evolution and evaluate output from complex ice sheet models
- 4. Analyze modern cryospheric datasets to quantify cryospheric processes and to recognize the limits of our knowledge about cryospheric evolution in a changing climate

**GPGN574. ADVANCED HYDROGEOPHYSICS. 0-3 Semester Hr.**
(II) Application of geophysical methods to groundwater problems from the grain scale to the basin scale. course introduces the groundwater flow and solute transport equations to understand the parameters controlling flow. Geophysical and numerical modeling techniques are introduced as a means to constrain transport parameters. Geophysical topics include electrical methods, seismic methods, downhole logging, and nuclear magnetic resonance. Modeling techniques include forward and inversion approaches for groundwater flow, solute transport, and geophysical data. Readings and discussions will be used to bring state-of-the-art applications of course content. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- NA

**GPGN577. HUMANITARIAN GEOSCIENCE. 3.0 Semester Hrs.**
(II) This interdisciplinary course introduces the concepts and practice of geoscientific investigations in humanitarian projects. Students will evaluate humanitarian geoscience case studies, devise the characteristics of successful projects, and identify how these best practices could improve previous case studies. This knowledge will be applied towards a group project. Students will split into groups and pair up with a faculty advisor and a local organization (e.g., NGO or community group) to design, execute and assess the impact of their project. A key emphasis in all aspects of the course will be on community engagement. This course is taught in collaboration with the Mines Engineering Design and Society Division and other participating departments.
**Course Learning Outcomes**

- Analyze humanitarian geoscience projects using established evaluation criteria
- Identify the most successful practices for humanitarian geoscience projects
- Determine different ways in which previous humanitarian geoscience projects could have been improved to yield more successful technical and social results
- Determine the most practical geoscientific methods for different humanitarian applications
- Work within a team to design, execute and evaluate a project with a local community organization
- Gain experience in engaging and communicating with community members and stakeholders
- Develop stronger professional communication skills through written assignments, group projects, discussions, presentations, and community engagement

**GPGN581. GRADUATE SEMINAR. 0-1 Semester Hr.**
(I, II) Attendance at scheduled weekly Heiland Distinguished Lectures during each semester of enrollment. Graduate students in Geophysics and Geophysical Engineering register each semester in residence in the program and receive 0.0 credit hours until the last semester in residence. For the last semester, 1.0 credit hours and a grade of PRG are awarded with satisfactory attendance.
**Course Learning Outcomes**

- Graduates will contribute to the advancement of their chosen fields through adopting, applying and evaluating state-of-the-art practices.
- Graduates will be viewed within their organizations as technologically advanced and abreast of the latest scholarship.

**GPGN583. READING SEMINAR. 1.0 Semester Hr.**
This course is designed to broaden the knowledge and perspective of MS students through reading and critiquing scientific publications. Student will read a scientific publication weekly that is related to the Heiland lecture of the week. Every week a student will present and lead the discussion of the paper during the class. Every student need to write a short discussion/summary/thinking/report after the Heiland lecture and post it on Canvas.
**Course Learning Outcomes**

**GPGN590. INSTRUMENTAL DESIGN IN APPLIED GEOSCIENCES. 3.0 Semester Hrs.**
A hands-on course on instrumental design for those interested in developing “sensors and software” solutions for use in applied geoscience and related engineering disciplines, including environmental, civil, electrical, mining, petroleum, and mechanical engineering. The first half of the course focuses on developing required skill sets in electronics microcomputers and device connectivity that enables students to construct a smart sensing system that is remotely accessible through the internet of things (IoT). The second half of the course consists of project work on multidisciplinary teams who devise, build, and validate usable prototype devices such as a magnetometer, a telemetered sap-monitoring unit, an autonomous ground penetrating radar, or a smart irrigation system. Prerequisite: CSCI250 or instructor consent.
**Course Learning Outcomes**

- Have an ability to apply knowledge of mathematics, science and engineering
- Have an ability to design and conduct experiments, as well as to analyze and interpret data
- Have an ability to communicate effectively
- Have an ability to analyze, quantitatively, the errors, limitations, and uncertainties in data

**GPGN597. SUMMER PROGRAMS. 0-12 Semester Hr.**

**GPGN598. SPECIAL TOPICS IN GEOPHYSICS. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**GPGN598. SPECIAL TOPICS. 0-6 Semester Hr.**

**GPGN598. SPECIAL TOPICS. 0-6 Semester Hr.**

**GPGN598. SPECIAL TOPICS. 0-6 Semester Hr.**

**GPGN599. GEOPHYSICAL INVESTIGATIONS MS. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**GPGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

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**GPGN651. ADVANCED SEISMOLOGY. 3.0 Semester Hrs.**
In-depth discussion of wave propagation and seismic processing for anisotropic, heterogeneous media. Topics include influence of anisotropy on plane-wave velocities and polarizations, traveltime analysis for transversely isotropic models, anisotropic velocity-analysis and imaging methods, point-source radiation and Green's function in anisotropic media, inversion and processing of multicomponent seismic data, shear-wave splitting, and basics of seismic fracture characterization. Prerequisite: GPGN552, GPGN553.

**GPGN658. SEISMIC WAVEFIELD IMAGING. 3.0 Semester Hrs.**
(I) Seismic imaging is the process that converts seismograms, each recorded as a function of time, to an image of the earth's subsurface, which is a function of depth below the surface. The course emphasizes imaging applications developed from first principles (elastodynamics relations) to practical methods applicable to seismic wavefield data. Techniques discussed include reverse-time migration and migration by wavefield extrapolation, angle-domain imaging, migration velocity analysis and analysis of angle-dependent reflectivity. Students do independent term projects presented at the end of the term, under the supervision of a faculty member or guest lecturer. Prerequisite: none. 3 hours lecture; 3 semester hours.

**GPGN698. SPECIAL TOPICS. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**GPGN699. GEOPHYSICAL INVESTIGATION-PHD. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**GPGN699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**GPGN699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**GPGN707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.**
(I, II, S) Research credit hours required for completion of a Masters-level thesis or Doctoral dissertation. Research must be carried out under the direct supervision of the student's faculty advisor. Variable class and semester hours. Repeatable for credit.

**SYGN501. RESEARCH SKILLS FOR GRADUATE STUDENTS. 1.0 Semester Hr.**
(I, II) This course consists of class sessions and practical exercises. The content of the course is aimed at helping students acquire the skills needed for a career in research. The class sessions cover topics such as the choice of a research topic, making a work plan and executing that plan effectively, what to do when you are stuck, how to write a publication and choose a journal for publication, how to write proposals, the ethics of research, the academic career versus a career in industry, time-management, and a variety of other topics. The course is open to students with very different backgrounds; this ensures a rich and diverse intellectual environment. Prerequisite: None. 1 hour lecture; 1 semester hour.
**Course Learning Outcomes**

- n/a

## Professors Emeriti

Thomas L. Davis

Dave Hale

Kenneth L. Larner

Gary R. Olhoeft

Phillip R. Romig, Jr.

Terence K. Young

## Emeritus Associate Professor

Thomas M. Boyd

## Professors

John H. Bradford, Vice President for Global Initiatives

Brandon Dugan, Associate Department Head, Baker Hughes Chair of Petrophysics and Borehole Geophysics

Yaoguo Li

Paul C. Sava, Department Head, C.H. Green Chair of Exploration Geophysics

Jeffrey C. Shragge

Ilya D. Tsvankin

## University Distinguished Professors

Kamini Singha

Ilya D. Tsvankin

## Associate professors

Ge Jin

Eileen Martin

Matthew Siegfried

## Assistant Professors

Bia Villas Bôas

Roslynn King

## Joint appointments with loci within Geophysics

Eileen Martin, Associate Professor in Applied Mathematics and Statistics

## Joint appointments with loci outside of Geophysics

Eric Anderson, Associate Professor, Civil and Environmental Engineering

Ebru Bozdag, Associate Professor, Applied Mathematics and Statistics

Elizabeth Reddy, Assistant Professor, Engineering, Design and Society

Kamini Singha, Professor, Geology and Geological Engineering

## Research Associate Professor

Richard Krahenbuhl

## Research Assistant Professor

Mengli Zhang

## Affiliate Faculty

Jyoti Behura, Founder & CEO, Seismic Science LLC

Timothy Collett, Senior Scientist, US Geological Survey

Morgan Moschetti, Research Geophysicist, US Geological Survey

Ryan North, Principal Geophysicist, ISC Geoscience

Nathaniel Putzig, Senior Scientist, Planetary Science Institute

Andrei Swidinsky, Associate Professor, University of Toronto

Whitney Trainor-Guitton, Geoscience Researcher, National Renewable Energy Laboratory

David Wald, Research Geophysicist, US Geological Survey

## Joint Appointments

Fred Day-Lewis, Chief Geophysicist, Pacific Northwest National Laboratory

# Humanities, Arts, and Social Sciences

## Degree Offered

- Master of Science in Environment, Resources & Energy Policy (non-thesis)

## Certificates Offered

- Graduate Certificate in Natural Resources and Energy Policy

## Minors Offered

- Graduate Individual Minor – A 12-credit minor for graduate students pursuing degrees in other Mines academic units. Please contact either a Humanities, Arts, and Social Sciences faculty member with whom you are interested in working or the director of the ENREP program. Minor must be approved by the student's graduate committee and by the ENREP Director.

## Program Description

The MS in Environment, Resources & Energy Policy (ENREP) is an interdisciplinary degree based in the Department of Humanities, Arts, and Social Sciences that trains students to be sociotechnical problem-solvers in the public policy domain. Through core courses that build a foundation in environmental, resource, and energy policy; skills courses that sharpen students' analytical and methodological toolkits; and electives from across campus that allow students to build expertise in their desired policy focus areas, students learn how to:

- Make thoughtful decisions about the future amidst social, political, environmental and technological change, as well as scientific uncertainty.
- Meaningfully engage diverse communities in policy processes and decision-making about the environment, resources, and energy.
- Analyze policy from multiple perspectives and with attention to multiple criteria, such as distributions of benefits and burdens, tradeoffs, risk, and more.
- Become leaders in the energy transition and climate change mitigation and adaptation, and recognize how these dynamics intersect other environment and resource topics.
- Communicate clearly, eloquently, and creatively in multiple professional formats and to different audiences.

Open to all undergraduate degrees and new graduates as well as early- and mid-career professionals, ENREP bridges disciplines and teaches both qualitative and quantitative skills. The program is research and writing intensive with a strong focus on verbal and written communication. Small classes allow faculty to connect with individual interests.

ENREP prepares students for jobs in government (local, state, and federal), consulting, non-profits and non-governmental organizations, the private sector, and academia. Drawing on Mines' international reputation and on-campus networking opportunities, graduates find jobs in water management, environmental compliance, energy analytics, community outreach, sustainability strategy, energy development, climate resilience, and other areas.

> This is a non-thesis MS program, requiring 30 credit-hours of coursework: 15 credit-hours in the core, and 15 hours of electives. It usually takes 1.5 years (3 semesters, including summer) to complete the program on a full-time basis.

Combined Undergraduate/Graduate Degree Programs

Mines students may earn the master's degree as part of Mines' Combined Undergraduate/Graduate program. Please note that Mines students interested in pursuing a Combined Undergraduate/Graduate program are encouraged to make an initial contact with the NREP director after the first semester of their sophomore year for counseling on application procedures, admissions standards, and degree completion requirements.

See Combined Undergraduate/Graduate Degree Programs elsewhere in this bulletin for further details.

## Admission Requirements

The requirements for admission into Humanities, Arts, and Social Sciences Graduate Programs are as follows*:*

1. An undergraduate degree (engineering, social sciences, and others accepted) with a cumulative grade-point average (GPA) at or above 3.0 (4.0 scale) or be a Mines undergraduate with a minimum GPA of 3.0 in the Humanities, Arts and Social Sciences coursework.
2. For students whose native language is not English, Mines requires a minimum TOEFL score of 79 internet-based test (iBT) or 550 paper-based test (PBT). Tests must have been taken within the past two

years to be accepted. *If you have completed a university degree program in the United States or in an English-speaking country within the previous two years, you do NOT have to submit TOEFL scores.*

## Program Requirements

## Master of Science in Environment, Resources & Energy Policy (ENREP, Non-Thesis)

The ENREP degree prepares students from multiple disciplinary backgrounds (in the social sciences and engineering) to be leaders in policy and problem-solving in the interconnected domains of environment, resources, and energy. The core curriculum engages a range of ENREP topics while offering foundational training in environment-society and resource relations, social and political change, public engagement, and policy dynamics. A variety of skills courses allow students to build further expertise in policy-relevant analytical skills to suit their desired career paths. Electives center around themes of interest to ENREP students that are also strengths of Mines faculty, including the energy transition and climate change, water management, environmental futures, international development, and more. Students engage in research- and writing-intensive assignments with a strong focus on verbal and written communication skills.

Designed for early or midcareer professionals, ENREP graduates typically find jobs in environmental, energy, or resource management/policy at the state, federal, local or international levels; environmental or energy consulting; and energy development in various forms. Additional career paths include positions at non-profit or non-governmental organizations, government affairs, community development, academia, and more.

This is a non-thesis program, requiring 30 credit hours of coursework: 15 credit hours in the core, and 15 hours of electives. As a full-time student, it generally takes 1.5 years (three semesters) to complete the program.

## Core: Foundations Courses (9 credits)

| | | |
|---|---|---|
| HASS578 | GLOBAL ENVIRONMENTAL ISSUES | 3.0 |
| HASS584 | US WATER POLITICS AND POLICY | 3.0 |
| MNGN571 | ENERGY, NATURAL RESOURCES, AND SOCIETY | 3.0 |
| **Total Semester Hrs** | | **9.0** |

## Core: Skills Courses (choose any two; 6 credits)

| | | |
|---|---|---|
| **Analytics & Modeling** | | |
| EBGN590 | ECONOMETRICS I | 3.0 |
| GEGN532 | GEOLOGICAL DATA ANALYSIS | 3.0 |
| GEGN575 | APPLICATIONS OF GEOGRAPHIC INFORMATION SYSTEMS | 3.0 |
| GEGN580 | APPLIED REMOTE SENSING FOR GEOENGINEERING AND GEOSCIENCES | 3.0 |
| MATH530 | INTRODUCTION TO STATISTICAL METHODS | 3.0 |
| **Community Engagement** | | |
| EDNS479 | COMMUNITY-BASED RESEARCH | 3.0 |
| HASS526 | INTERCULTURAL COMMUNICATION | 3.0 |
| HASS527 | RISK COMMUNICATION | 3.0 |
| HASS550 | POLITICAL RISK ASSESSMENT | 3.0 |
| HASS568 | ENVIRONMENTAL JUSTICE | 3.0 |
| **Sustainability** | | |
| CEEN501 | LIFE CYCLE ASSESSMENT | 3.0 |
| CEEN595 | ANALYSIS OF ENVIRONMENTAL IMPACT | 3.0 |
| HASS525 | ENVIRONMENTAL COMMUNICATION | 3.0 |
| PEGN530 | ENVIRONMENTAL LAW AND SUSTAINABILITY | 3.0 |
| **History & Theory** | | |
| EDNS515 | INTRODUCTION TO SCIENCE AND TECHNOLOGY STUDIES | 3.0 |
| HASS521 | ENVIRONMENTAL PHILOSOPHY | 3.0 |

## Electives (15 credits)

Pre-approved electives are organized here by theme. Students may take electives from any department, but note that some courses have prerequisites or are primarily for engineers in those fields. In those cases, students should check with the professor before taking the course. Because electives are constantly evolving, students are encouraged to review current offerings each semester. Skills courses beyond the two required also count as electives. Students may want to consider adding a minor in a related discipline that overlaps their electives.

**Energy Transition**

| | | |
|---|---|---|
| HASS590 | ENERGY AND SOCIETY | 3.0 |
| HASS591 | ENERGY TRANSITION: POLITICS & POLICY | 3.0 |
| EBGN502 | POLITICAL ECONOMY OF THE ENERGY TRANSITION | 3.0 |
| EBGN521 | MICROECONOMICS OF MINERAL AND ENERGY MARKETS | 3.0 |

**Environmental Futures**

| | | |
|---|---|---|
| HASS521 | ENVIRONMENTAL PHILOSOPHY | 3.0 |
| HASS525 | ENVIRONMENTAL COMMUNICATION | 3.0 |
| HASS568 | ENVIRONMENTAL JUSTICE | 3.0 |
| HASS587 | ENVIRONMENTAL POLITICS AND POLICY | 3.0 |
| HASS588 | GLOBAL WATER POLITICS AND POLICY | 3.0 |
| CEEN573 | RECLAMATION OF DISTURBED LANDS | 3.0 |
| CEEN575 | HAZARDOUS WASTE SITE REMEDIATION | 3.0 |
| CEEN597 | PRACTICES AND PRINCIPLES OF ENVIRONMENTAL CONSULTING | 3.0 |

**International Development**

| | | |
|---|---|---|
| HASS535 | INTERNATIONAL DEVELOPMENT | 3.0 |
| HASS541 | AFRICAN DEVELOPMENT | 3.0 |
| HASS560 | GEOPOLITICS OF NATURAL RESOURCES | 3.0 |
| HASS591 | ENERGY TRANSITION: POLITICS & POLICY | 3.0 |

**Minerals & Mining**

| | | |
|---|---|---|
| CEEN556 | MINING AND THE ENVIRONMENT | 3.0 |
| CEEN573 | RECLAMATION OF DISTURBED LANDS | 3.0 |
| MNGN510 | FUNDAMENTALS OF MINING AND MINERAL RESOURCE DEVELOPMENT | 3.0 |
| MNGN546 | MINE HEALTH AND SAFETY | 2.0 |
| MNGN557 | MINERAL ECONOMICS AND POLICY | 2.0 |

| | | |
|---|---|---|
| MNGN562 | MINING ENVIRONMENTAL AND SOCIAL RESPONSIBILITY | 2.0 |

**Economics & Policy**

| | | |
|---|---|---|
| EBGN509 | MATHEMATICAL ECONOMICS | 3.0 |
| EBGN510 | NATURAL RESOURCE ECONOMICS | 3.0 |
| EBGN521 | MICROECONOMICS OF MINERAL AND ENERGY MARKETS | 3.0 |
| EBGN530 | ECONOMICS OF INTERNATIONAL ENERGY MARKETS | 3.0 |
| EBGN535 | ECONOMICS OF METAL INDUSTRIES AND MARKETS | 3.0 |
| EBGN537 | ECONOMICS OF WATER | 3.0 |
| EBGN594 | TIME-SERIES ECONOMETRICS | 3.0 |

**Professional Development**

| | | |
|---|---|---|
| EBGN553 | PROJECT MANAGEMENT | 3.0 |
| LICM501 | PROFESSIONAL ORAL COMMUNICATION | 1.0 |
| SYGN598 | SPECIAL TOPICS (PAID INTERNSHIP) | 3.0 |
| SYGN501 | RESEARCH SKILLS FOR GRADUATE STUDENTS | 1.0 |
| SYGN502 | INTRODUCTION TO RESEARCH ETHICS | 1.0 |
| SYGN503 | TOOLS FOR SUCCESS: INTEGRATING INTO THE MINES COMMUNITY | 1.0 |
| SYGN683 | ORAL COMMUNICATION SKILLS | 1.0 |
| SYGN684 | WRITING SKILLS | 2.0 |

## Mines' Combined Undergraduate / Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must be taken at the 500-level, have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit. Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

## Program Requirements

## Graduate Certificate in Natural Resources and Energy Policy

Designed to be completed in a single semester, or over two semesters for part-time students, the Certificate in Natural Resources and Energy Policy (NREP) is a 9-credit program affiliated with the MS in NREP.

To earn the certificate, students must take two of the five required courses for the Master's program plus an elective to be approved by the NREP Director:

| | | |
|---|---|---|
| HASS593 | NATURAL RESOURCES & ENERGY POLICY: THEORIES AND PRACTICE | 3.0 |
| PEGN530 | ENVIRONMENTAL LAW AND SUSTAINABILITY | 3.0 |
| MNGN571 | ENERGY, NATURAL RESOURCES, AND SOCIETY | 3.0 |
| HASS550 | POLITICAL RISK ASSESSMENT | 3.0 |
| QUANT | QUANTITATIVE METHODS ELECTIVE | |

Approved Quantitative Methods list:

| | | |
|---|---|---|
| EBGN590 | ECONOMETRICS I | 3.0 |
| MATH530 | INTRODUCTION TO STATISTICAL METHODS | 3.0 |
| MNGN565 | MINE RISK MANAGEMENT | 3.0 |
| GEGN532 | GEOLOGICAL DATA ANALYSIS | 3.0 |
| GEGN575 | APPLICATIONS OF GEOGRAPHIC INFORMATION SYSTEMS | 3.0 |

## Courses

**HASS521. ENVIRONMENTAL PHILOSOPHY. 3.0 Semester Hrs.**
Equivalent with LAIS521,
Analyzes environmental ethics and philosophy including the relation of philosophical perspectives to policy decision making. Critically examines often unstated ethical and/or philosophical assumptions about the environment and how these may complicate and occasionally undermine productive policies. Policies that may be considered include environmental protection, economic development, and energy production and use. 3 hours seminar; 3 semester hours.
**Course Learning Outcomes**

**HASS523. ADVANCED SCIENCE COMMUNICATION. 3.0 Semester Hrs.**
Equivalent with LAIS523,
This course will examine historical and contemporary case studies in which science
communication (or miscommunication) played key roles in shaping policy outcomes and/or public perceptions. Examples of cases might include the recent controversies over hacked climate science emails, nuclear power plant siting controversies, or discussions of ethics in classic environmental cases, such as the Dioxin pollution case. Students will study, analyze, and write about science communication and policy theories related to scientific uncertainty; the role of the scientist as communicator; and media ethics. Students will also be exposed to a number of strategies for managing their encounters with the media, as well as tools for assessing their communication responsibilities and capacities. 3 hours seminar; 3 semester hours.

**HASS525. ENVIRONMENTAL COMMUNICATION. 3.0 Semester Hrs.**
Equivalent with LAIS525,
(I, II, S) This course explores the ways that messages about the environment and environmentalism are communicated in the mass media, fine arts, and popular culture. The course will introduce students to key readings in environmental communication, media studies, and cultural studies in order to understand the many ways in which the images, messages, and politics of environmentalism and the natural world are constructed and contested by diverse audiences. Students will critically analyze their roles as science and/or technology communicators in the context of environmental issues, and will apply their skills to creating communications projects for diverse audiences. 3 lecture hours, 3 semester hours.
**Course Learning Outcomes**

- Identify major events, themes, and concepts, and narratives that have shaped the modern environmental movement and societal understandings of environmentalism
- Analyze environmental debates in both academic discourse and popular culture

- Understand and engage critically with the roles that scientists and engineers play as communicators in environmental debates
- Research and develop professional written products that make strong and logical arguments using primary and secondary sources
- Sharpen oral communication and presentation skills

**HASS526. INTERCULTURAL COMMUNICATION. 3.0 Semester Hrs.**
The course examines intercultural communication theory and practice. In particular, the course provides students with a window into how intercultural (mis)communication cases arise, evolve, and are resolved. Students investigate communication cases and issues across a broad range of cultural divides, such as national, gender, social class, and racial/ethnic cultures. Some case studies are situated in engineering and applied science contexts.
**Course Learning Outcomes**

**HASS527. RISK COMMUNICATION. 3.0 Semester Hrs.**
How do people perceive risk, as well as make decisions and communicate under conditions of uncertainty and risk? This course explores multiple perspectives on that overarching question. Although risk perception, risk management, and risk communication are three major course components, they are not treated separately but in terms of how they interrelate. Case studies include engineers and applied scientists coping with complex forms of uncertainty and risk, communicating in organizational and public sphere contexts with multiple audiences via the press and directly to the public, stockholders, co-workers, local communities, and more. In addition, students will critically reflect on the social consequences of living with risk in our contemporary moment.
**Course Learning Outcomes**

**HASS535. INTERNATIONAL DEVELOPMENT. 3.0 Semester Hrs.**
Equivalent with LAIS535,
(I, II, S) Explores the political economy of current and recent-historical development strategies, models, efforts, and issues in various world regions. The class will focus on Africa, Asia, Eurasia, Latin America, or the Middle East, depending on the semester. Development is understood to be a nonlinear, complex set of processes involving political, economic, social, cultural, and environmental factors whose ultimate goal is to improve the quality of life for individuals. Students will explore the roles of governments, companies, organizations, and individuals. Exact topics to be covered will vary with current events and the specific region; topics might include income inequality, the role of national and private energy companies, the impact of globalization, the role of development aid, and concepts of good governance. Students may take the course up to three times, covering different regions. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- N/A

**HASS541. AFRICAN DEVELOPMENT. 3.0 Semester Hrs.**
Equivalent with LAIS541,
Provides a broad overview of the political economy of Africa. Its goal is to give students an understanding of the possibilities of African development and the impediments that currently block its economic growth. Despite substantial natural resources, mineral reserves, and human capital, most African countries remain mired in poverty. The struggles that have arisen on the continent have fostered thinking about the curse of natural resources where countries with oil or diamonds are beset with political instability and warfare. Readings give first an introduction to the continent followed by a focus on the specific issues that confront African development today. 3 hours lecture and discussion; 3 semester hours.

**HASS550. POLITICAL RISK ASSESSMENT. 3.0 Semester Hrs.**
Equivalent with LAIS550,
Uses social science analytical tools and readings as well as indices prepared by organizations, such as the World Bank and the International Monetary Fund, to create assessments of the political, social, economic, environmental and security risks that multinational corporations may face as they expand operations around the world. Students will develop detailed political risk reports for specific countries that teams collectively select. Prerequisite: HASS 545 and IPE Minor. 3 hours seminar; 3 semester hours.

**HASS560. GEOPOLITICS OF NATURAL RESOURCES. 3.0 Semester Hrs.**
Equivalent with LAIS560,
This seminar examines geopolitical competition between great and aspiring powers for influence, control over land and natural resources, critical geo-strategic trade routes, or even infrastructure. Using empirical evidence from case studies, students develop a deeper understanding of the interconnections between the political, economic, social, cultural and geographic dimensions of foreign policies, as well as issues of war and peace.

**HASS565. SCIENCE, TECHNOLOGY, AND SOCIETY. 3.0 Semester Hrs.**
Equivalent with LAIS565,
Provides an introduction to foundational concepts, themes, and questions developed within the interdisciplinary field of science and technology studies (STS). Readings address anthropological understandings of laboratory practice, sociological perspectives on the settling of techno-scientific controversies, historical insights on the development of scientific institutions, philosophical stances on the interactions between technology and humans, and relationships between science and democracy. Students complete several writing assignments, present material from readings and research, and help to facilitate discussion. 3 hours lecture and discussion; 3 semester hours.

**HASS568. ENVIRONMENTAL JUSTICE. 3.0 Semester Hrs.**
This course explores the history of the environmental justice movement, current and emerging environmental justice issues, and the application of environmental justice concepts and theories to environmental decision-making. Course content and activities are designed to enrich student understanding of how environmental injustice is produced (locally, regionally, and globally), how environmental justice issues are measured and analyzed, and how environmentally just outcomes can be achieved.
**Course Learning Outcomes**

**HASS578. GLOBAL ENVIRONMENTAL ISSUES. 3.0 Semester Hrs.**
Examines global issues in environment-society interactions using analytical tools and methodological approaches from the humanities, arts, and/or social sciences. Students will gain critical perspectives on global environmental problems and solutions with an emphasis on their interrelated social, political, economic, and cultural elements.
**Course Learning Outcomes**

- Analyze contemporary global environmental issues and how those issues intersect social, political, and/or cultural systems.
- Critically evaluate proposed solutions to global environmental issues.
- Conduct individual research and communicate findings in ways that are effective for public and policy audiences.

**HASS584. US WATER POLITICS AND POLICY. 3.0 Semester Hrs.**
(I) The story of water in the American West is one of engineering and applied science inextricably intertwined with a "Gordian knot" of law and policy, changing social and cultural values, and increasingly

unpredictable hydrology. This course will familiarize students with the complexities of contemporary water governance, using the Colorado River system as its central case study. The Colorado River makes for an excellent point of departure because it is one of the most dammed, diverted, legislated, litigated, and loved rivers in the world and because we literally use it up; the river has seldom reached the sea since the 1960s. Indeed, the challenges that face the Colorado River's 40 million stakeholders today have less to do with applying law and engineering to developing water resources, and much more to do with figuring out how to share an over-appropriated resource while mitigating the social and ecological consequences of past choices. Our primary goal in the course will be to learn concepts of adaptive governance that provide a constructive and framework for analyzing and addressing such challenges. 3 hours lecture; 3 semester hours.

**Course Learning Outcomes**

- Demonstrate an understanding of contemporary water politics and policy in the arid American West

**HASS586. SCIENCE AND TECHNOLOGY POLICY. 3.0 Semester Hrs.**

Equivalent with LAIS586,

Examines current issues relating to science and technology policy in the United States and, as appropriate, in other countries. 3 hours lecture and discussion; 3 semester hours.

**HASS587. ENVIRONMENTAL POLITICS AND POLICY. 3.0 Semester Hrs.**

Equivalent with LAIS587,

Explores environmental policies and the political and governmental processes that produce them. Group discussion and independent research on specific environmental issues. Primary but not exclusive focus on the U.S. 3 hours lecture and discussion; 3 semester hours.

**HASS588. GLOBAL WATER POLITICS AND POLICY. 3.0 Semester Hrs.**

Equivalent with LAIS588,

(II) This interdisciplinary seminar course analyzes how droughts, floods, water management, global trading system, and climate change affect the hydrological and food systems that are critically important for economic prosperity and political stability. It addresses water policy at scales that range from community level to global governance regimes. It uses relevant analytical perspectives of, for example, psychology, political economy, development studies, and institutional approaches in economic geography to help students understand how certain transboundary water conflicts have emerged, their national and regional implications, and policies and institutions that can be used to resolve them. 3 hours lecture; 3 semester hours.

**Course Learning Outcomes**

- Understand key issues in water politics and policy in the Middle East

**HASS590. ENERGY AND SOCIETY. 3.0 Semester Hrs.**

Equivalent with LAIS590,

(II) The course begins with a brief introduction to global energy production and conservation, focusing on particular case studies that highlight the relationship among energy, society, and community in different contexts. The course examines energy successes and failures wherein communities, governments, and/or energy companies come together to promote socially just and economically viable forms of energy production/conservation. The course also explores conflicts driven by energy development. These case studies are supplemented by the expertise of guest speakers from industry, government, NGOs, and elsewhere. Areas of focus include questioning the forward momentum of energy production, its social and environmental impact, including how it distributes power, resources and risks across different social groups and communities. 3 hours seminar; 3 semester hours.

**HASS591. ENERGY TRANSITION: POLITICS & POLICY. 3.0 Semester Hrs.**

We will use social science approaches, theories, and methods to investigate the global, regional, state, and local politics of the energy transition, moving away from carbon-intensive sources to renewable and cleaner sources, including wind, solar, hydro, and nuclear power. We will look at the politics behind energy in the United States and several other countries and critically assess national and global policies to hasten the transition. Guest speakers, videos, and other course content will represent views from energy companies, non-governmental organizations, university and research entities, government representatives, and local activists. 3 lecture hours, 3 semester hours.

**Course Learning Outcomes**

- Compare and contrast the pros and cons of various energy sources combining energy and social science concepts such as energy density, energy security, intermittency, infrastructure costs, jobs, inter alia.
- Create an energy transition plan from fossil fuels to clean energy using energy concepts that addresses political challenges and opportunities and demonstrates knowledge of different policy instruments and how policy is made in the United States
- Compare energy production and consumption (by type of resource, amount per capita, etc.) of several countries, including at least one country in Asia and one in Africa. Assess what these differences mean for global governance of the energy transition.
- Apply social science and energy concepts to news articles from energy-focused sources.
- Differentiate between different types of research sources and when best to use each one.
- Apply professional communication best practices in written and oral forms.
- Create a research design.

**HASS593. NATURAL RESOURCES & ENERGY POLICY: THEORIES AND PRACTICE. 3.0 Semester Hrs.**

(I) This course introduces students to the policy-making process, drawing on a variety of theoretical approaches, geographic locations (within the US and in other countries), and resources and energy issues. Coordinated by the NREP Graduate Director, speakers will be from HASS, Economics and Business, Petroleum Engineering, Mining, and other departments with policy expertise, as well as from others who influence and create public and private policy. In the second half of the course, students will conduct original research projects that focus on natural resources and energy, applying theoretical frameworks they have learned from the speakers. 3 lecture hours, 3 semester hours.

**Course Learning Outcomes**

- Identify and apply major theoretical approaches to policy
- Prepare clear and persuasive short policy briefings on natural resources and energy issues

**HASS598. SPECIAL TOPICS. 0-6 Semester Hr.**

Equivalent with LAIS598A,

(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**HASS598. SPECIAL TOPICS. 0-6 Semester Hr.**
Equivalent with LAIS598B,
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**HASS598. SPECIAL TOPICS. 0-6 Semester Hr.**
Equivalent with LAIS598C,
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**HASS598. SPECIAL TOPICS. 0-6 Semester Hr.**
Equivalent with LAIS598D,
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**HASS598. SPECIAL TOPICS. 0-6 Semester Hr.**
Equivalent with LAIS598E,
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**HASS598. SPECIAL TOPICS. 0-6 Semester Hr.**
Equivalent with LAIS598F,
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**HASS598. SPECIAL TOPICS. 0-6 Semester Hr.**
Equivalent with LAIS598G,
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**HASS599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
Equivalent with LAIS599A,
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**HASS599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
Equivalent with LAIS599B,
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**HASS599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
Equivalent with LAIS599C,
.

**HASS599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
Equivalent with LAIS599D,
.

**HASS599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
Equivalent with LAIS599E,
.

**HASS599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
Equivalent with LAIS599F,
.

**HASS599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
Equivalent with LAIS599G,
.

**HASS599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
Equivalent with LAIS599H,
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**HASS599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
Equivalent with LAIS599I,
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**HASS599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
Equivalent with LAIS599J,
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**HASS599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
Equivalent with LAIS599K,
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**HASS599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
Equivalent with LAIS599L,
.

**HASS599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
Equivalent with LAIS599M,
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**HASS599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
Equivalent with LAIS599N,
.

**HASS599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
Equivalent with LAIS599O,
.

**HASS599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
Equivalent with LAIS599P,
.

**HASS601. ACADEMIC PUBLISHING. 2-3 Semester Hr.**
Equivalent with LAIS601,
Students will finish this course with increased knowledge of general and discipline - specific writing conversations as well as the ability to use that knowledge in publishing portions of theses or dissertations. Beyond the research article, students will also have the opportunity to learn more about genres such as conference abstracts, conference presentations, literature reviews, and research funding proposals. Prerequisite: Must have completed one full year (or equivalent) of graduate school course work. Variable credit: 2 or 3 semester hours.

**HASS698. SPECIAL TOPICS. 0-6 Semester Hr.**
Equivalent with LAIS698A,
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**HASS699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
Equivalent with LAIS699A,
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**HASS707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.**
Equivalent with LAIS707,
(I, II, S) GRADUATE THESIS/DISSERTATION RESEARCH CREDIT Research credit hours required for completion of a Masters-level thesis or Doctoral dissertation. Research must be carried out under the direct supervision of the student's faculty advisor. Variable class and semester hours. Repeatable for credit.

**LICM501. PROFESSIONAL ORAL COMMUNICATION. 1.0 Semester Hr.**
A five-week course which teaches the fundamentals of effectively preparing and presenting messages. "Hands-on" course emphasizing short (5- and 10-minute) weekly presentations made in small groups to simulate professional and corporate communications. Students are encouraged to make formal presentations which relate to their academic or professional fields. Extensive instruction in the use of

visuals. Presentations are rehearsed in class two days prior to the formal presentations, all of which are video-taped and carefully evaluated. 1 hour lecture/lab; 1 semester hour.

## Professors

Hussein A. Amery

Lucas Bessire

Jon A. Leydens

Kenneth Osgood

## Associate Professors

Tina L. Gianquitto

Kathleen J. Hancock

Adrianne Kroepsch, NREP Graduate Program co-Director

James D. Straker

## Teaching Professors

Jonathan Cullison

Derrick Hudson, NREP Graduate Program co-Director

Paula A. Farca

Cortney Holles

Joseph Horan

Shannon Davies Mancus, Associate Department Head

Seth Tucker

Sandy Woodson, Department Head

## Teaching Associate Professors

Eliza Buhrer

Heather Fester

## Teaching Assistant Professors

Mairead Case

Masakazu Ito

Allison Kerr

Brianna Wolfe

## Hennebach Visiting Assistant Professor

Angeline Letourneau

## Professors Emeriti

W. John Cieslewicz

T. Graham Hereford

Carl Mitcham

Barbara M. Olds

Eul-Soo Pang

Anton G. Pegis

Thomas Philipose, University Emeritus Professor

Arthur B. Sacks

## Associate Professors Emeriti

Betty J. Cannon

John Heilbrunn

Kathleen H. Ochs

Laura J. Pang

Karen B. Wiley

## Teaching Professor Emeriti

James Jesudason

Robert Klimek

## Teaching Associate Emerti

Rose Pass

# Mechanical Engineering

## PROGRAM DESCRIPTION

The graduate program in Mechanical Engineering at Mines combines a strong foundation in engineering fundamentals with applied skills to solve real-world engineering problems. The Department offers the following degrees:

- Master of Science (Non-thesis: on-campus or online modalities available)
- Master of Science (Thesis)
- Doctor of Philosophy

The Department's course offerings and cutting-edge research are aligned with four core Mechanical Engineering focus areas: i) Biomechanics, ii) Robotics and Automation, iii) Solid Mechanics, Materials, and Manufacturing, and iv) Thermal, Fluids and Energy Systems. In many cases, student course work and thesis research encompass more than one research area and elements from other disciplines.

***Biomechanics*** applies engineering principles to living things, with a primary focus on the musculoskeletal system of the human body. Research in this area addresses rehabilitation engineering, patient-specific biomechanical modeling, assessment of human interaction with equipment, assistive devices, and implants, mobility and performance analysis, and bioinstrumentation. Research projects use advanced computational modeling and experimentation with human subjects.

***Robotics and Automation*** research areas apply innovative technologies to problems in robotics, robot-human interaction, manufacturing, and health care. Our research ranges from artificial intelligence to autonomous and remotely operated robot technologies, including applications in additive manufacturing, underground mine safety, medical and healthcare, space, and advanced control. We use both high-performance computational and physical prototyping methods to advance research in these areas.

***Solid Mechanics, Materials, and Manufacturing*** research areas develop novel computational and experimental solutions for problems in the mechanical behavior of advanced materials and manufacturing. Research in the division spans multiple length scales, from the atomic up to the structural, unraveling the complex relationships between material microstructure, mechanical properties and performance. Our work includes development of state-of-the-art characterization and experimental techniques, advanced mechanical behavior models, and novel manufacturing process development.

***Thermal, Fluid and Energy Systems*** research areas address a wide array of cutting-edge topics that rely on thermodynamics, heat transfer, fluid mechanics, and chemical phenomena. Research uses advanced experimental diagnostics and numerical simulation tools to solve problems in a wide range of fields, including energy storage and conversion, sustainable transportation and fuels, water purification and processing, and aerodynamics. Projects range in scope from characterization and modeling of molecular-scale processes to design and analysis of commercial-scale systems.

## Program Details

The Mechanical Engineering Department offers the degrees Master of Science and Doctor of Philosophy in Mechanical Engineering. The master's program is designed to prepare candidates for careers in industry or government or for further study at the PhD level; both thesis and non-thesis options are available. The PhD degree program is sufficiently flexible to prepare candidates for careers in industry, government, or academia. The following information provides details on these degrees.

## Mines's Combined Undergraduate / Graduate Degree Program

Students enrolled in Mines's combined undergraduate/graduate program may double count up to six credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. See Graduate section of the Catalog under *Combined Undergraduate/ Graduate Degree Programs for specific details on* what types of courses are allowed and under what conditions. These courses must have been passed with "B-" or better, must not be substitutes for required coursework, and must meet all other University, Department, and Program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

## Program Restrictions

*Transfer Courses:* Graduate-level courses taken at other universities and passed with a grade equivalent of "B" or better will be considered for transfer credit into the Mechanical Engineering Department. Approval from the Advisor and/or Thesis Committee and ME Department Head will be required as appropriate.

*Internships*: The Mechanical Engineering Graduate Program does not accept Internships (such as SYGN: 598I) for Graduate Credit.

## Master of Science Degree Requirements

The MS degree in Mechanical Engineering requires 30 credits. Requirements for the MS thesis option are 24 credits of coursework and 6 credits of thesis research. The MS non-thesis option requires 30 credits of coursework.

*Advisor and Thesis Committee:* Students must have an Advisor from the Mechanical Engineering Department Faculty to direct and monitor their academic plan, research, and independent studies. The MS graduate Thesis Committee must have at least three members, two of whom must be permanent faculty in the Mechanical Engineering Department.

## MS Non-Thesis Degree

| | | |
|---|---|---|
| MEGN502 | ADVANCED ENGINEERING ANALYSIS | 3.0 |
| ME CORE | Two courses from the Mechanical Engineering Core List | 6.0 |
| ME ELECTIVES | Any 500-level or above MEGN, AMFG, or FEGN courses | 12.0 |
| TECHNICAL ELECTIVES | Any 500-level or above courses | 9.0 |
| **Total Semester Hrs** | | **30.0** |

*Time Limit:* As stipulated by the Mines Graduate School, a candidate for a Masters degree must complete all requirements for the degree within five years of the date of admission into the degree program.

An online modality is also available for Masters Non-Thesis.

## MS Thesis Degree

| | | |
|---|---|---|
| MEGN502 | ADVANCED ENGINEERING ANALYSIS | 3.0 |
| MEGN503 | GRADUATE SEMINAR Enrollment required every Fall and Spring semester | 0.0 |
| ME CORE | Courses from the Mechanical Engineering Core List | 6.0 |
| ME ELECTIVES | Any 500-level or above MEGN, AMFG, or FEGN courses. | 9.0 |
| TECHNICAL ELECTIVES | Any 500-level or above courses (Approved by Advisor/Thesis Committee) | 6.0 |
| MEGN707 | GRADUATE THESIS / DISSERTATION RESEARCH CREDIT | 6.0 |
| **Total Semester Hrs** | | **30.0** |

*Thesis Defense*: At the conclusion of the MS Thesis Option, the student will be required to make a formal presentation and defense of their thesis research to their Advisor and Thesis Committee.

## Doctor of Philosophy Degree Requirements

The PhD degree in Mechanical Engineering requires 72 credits of coursework + research credits. A minimum of 30 credits of course work and 30 credits of research credits must be completed. A minimum of 12 of the 30 credits of required coursework must be taken at Colorado School of Mines.

| | | |
|---|---|---|
| MEGN502 | ADVANCED ENGINEERING ANALYSIS | 3.0 |
| MEGN503 | GRADUATE SEMINAR Enrollment required every Fall and Spring semester | 0.0 |
| ME CORE | Courses from the Mechanical Engineering Core List | 6.0 |
| TECHNICAL ELECTIVES | Technical Electives. Any 500-level or above courses approved by Advisor/Thesis Committee. | 21.0 |
| MEGN707 | GRADUATE THESIS / DISSERTATION RESEARCH CREDIT | 30.0 |

| | | |
|---|---|---|
| TOTAL CREDITS | Remaining 12 credits can come from Research and/or Technical Electives | 72.0 |

| MILESTONE | TIMELINE |
|---|---|
| Select a permanent advisor | Second semester |
| Complete the PhD qualifying examination | By the end of third semester |
| Complete all core curriculum course requirements | Fourth semester |
| Submit Degree Audit and Admission to Candidacy forms | By fifth semester |
| Establish a dissertation committee and present research proposal | By fifth semester |
| Present a preliminary defense | 12 months before dissertation defense |
| Present a dissertation defense | |

*Advisor and Thesis Committee:* Students must have an Advisor from the Mechanical Engineering Department Faculty to direct and monitor their academic plan, research, and independent studies. The PhD graduate Thesis Committee must have at least four members; at least two members must be permanent faculty in the Mechanical Engineering Department, and at least one member must be from outside the department. This outside member must chair the committee. Students who choose to have a minor program must select a representative from the minor areas of study to serve on the Thesis Committee.

*Qualifying Exam:* Students enrolled in the Mechanical Engineering PhD program will be required to pass a Qualifying Exam. PhD students with a minimum graduate grade point average of 3.0 are eligible to take the qualifying exam. Students must have completed at least four 500-level courses before taking the qualifier.

The Qualifying Exam assesses some attributes expected of a successful PhD student, including:

- ability to review, synthesize and apply fundamental concepts;
- creative and technical ability of the student to solve open-ended and challenging problems;
- technical communication skills.

Exam results of Pass, Conditional Pass or Fail will be provided to the student in a timely manner by the Qualifying Exam Chair. A Conditional Pass will require the student to take a remedial plan. Students have two attempts to pass the exam. If the student fails the exam on their first attempt, they must retake the exam in the following semester. One-semester extensions may be granted by the Qualifying Exam Chair.

*Research Proposal*: After passing the Qualifying Examination, the PhD student will prepare a written Research Proposal for the Dissertation and present it formally to the Dissertation Committee, which is selected by the student and the student's advisor and approved by the Department Head. This Research Proposal gives the Committee an early chance to discuss the work and to help the student more clearly define the work and identify the salient aspects. The research proposal must be completed before admission to candidacy.

*Degree Audit and Admission to Candidacy:* PhD students must complete the Degree Audit form by the posted deadlines and the Admission to Candidacy form by the first day of classes of the semester in which they want to be considered PhD candidates.

Additionally, full-time PhD students must complete the following requirements within the first two calendar years after enrolling into the PhD program:

- have a Thesis Committee appointment form on file in the Graduate Office;
- complete all prerequisite and core curriculum course requirements;
- pass the qualifier; and
- be admitted into full candidacy for the degree.

*Preliminary Defense:* Prior to the final Dissertation Defense, the PhD student will make an oral presentation to the student's Committee to summarize research accomplishments and remaining goals and work plan. This meeting serves as a final check to assess if the student's progress is on schedule for graduation. The student must give no more than a 45-minute presentation that summarizes the work already accomplished, including their relevant publication(s) and a proposed plan of the work needed to culminate in a formal defense and graduation. The Committee will provide feedback and, as necessary, revisions to the proposed work plan such that its completion should lead to a successful Dissertation Defense and publication record in a realistic time frame. The time period between the Research Proposal and the Preliminary Defense can span a few years, but the Preliminary Defense should take place 12 months and no less than 6 months prior to the date of Dissertation Defense.

*Required Number of Publications and Presentations:* The required and recommended journal publications for PhD students prior to graduation are listed below. Students wanting to defend before meeting these requirements must submit a one-page petition with a reasonable explanation to the ME Graduate Curriculum Committee.

Journal publications - *Required:* Minimum of one first-author paper accepted or published (DOI is required) in a peer-reviewed journal (recognized as high quality in the research field), before Dissertation Defense. *Recommended:* Three or more first-author papers accepted or published in peer-reviewed journals.

Presentations - *Required:* Minimum of one research presentation (poster or podium) at an external technical conference before the Dissertation Defense. *Recommended:* Two or more conference presentations (poster or podium), before the Dissertation Defense in which the student is the first author on these presentations.

*Thesis Defense:* At the conclusion of the student's PhD program, the student will make a formal presentation and defense of her/his thesis research. A student must pass this defense to earn a PhD degree. The Dissertation document should be submitted to the Dissertation Committee at least 10 days prior to the Defense. The Committee will perform a post-presentation review of the Dissertation, technical contributions, and publications with the student. The Committee may request revisions to the Dissertation and additional work that requires subsequent review by the advisor and or the Committee.

*Time Limit:* As stipulated by the Mines Graduate School, a candidate for a doctoral degree must complete all requirements for the degree within nine years of the date of admission into the degree program.

**MECHANICAL ENGINEERING CORE COURSES (ME CORE)**

| | | |
|---|---|---|
| MEGN505 | ADVANCED DYNAMICS | 3.0 |
| MEGN514 | CONTINUUM MECHANICS | 3.0 |
| MEGN551 | ADVANCED FLUID MECHANICS | 3.0 |
| MEGN571 | ADVANCED HEAT TRANSFER | 3.0 |

## Courses

**MEGN501. ADVANCED ENGINEERING MEASUREMENTS. 3.0 Semester Hrs.**
Equivalent with EGGN501,
Introduction to the fundamentals of measurements within the context of engineering systems. Topics that are covered include: errors and error analysis, modeling of measurement systems, basic electronics, noise and noise reduction, and data acquisition systems. Prerequisite: EENG281 or equivalent, and MATH201 or equivalent, Graduate student status.
**Course Learning Outcomes**

- Understand operational principles of many sensors.
- Be able to read and understand spec. sheets.
- Apply uncertainty analysis to experimental design and estimate order of magnitude of expected erros.
- Apply techniques for improving sensor system performance.
- Identify components needed for a sensor system and how each component affects the overall system performance.
- Understand how different measurement principles can be used to measure the same engineering values and apply physics understanding to find the most appropriate sensing options.
- Learn some experiment rules of thumb and basic troubleshooting skills.

**MEGN502. ADVANCED ENGINEERING ANALYSIS. 3.0 Semester Hrs.**
Introduce advanced mathematical and numerical methods used to solve engineering problems. Analytic methods include series solutions, special functions, Sturm-Liouville theory, separation of variables, and integral transforms. Numerical methods for initial and boundary value problems include boundary, domain, and mixed methods, finite difference approaches for elliptic, parabolic, and hyperbolic equations, Crank-Nicolson methods, and strategies for nonlinear problems. The approaches are applied to solve typical engineering problems. The student must have a solid understanding of linear algebra, calculus, ordinary differential equations, and Fourier theory.
**Course Learning Outcomes**

- Analytically solve higher-order constant coefficient Ordinary Differential Equations (ODEs).
- Solve systems of constant coefficient ODEs analytically and numerically.
- Categorize, solve and visualize solutions of variable coefficient ODEs with series solution methods.
- Develop a deep understanding of Sturm-Liouville problems by solving Bessel, Legendre and Equidimensional equations, and exploring the key characteristics of eigenfunctions.
- Solve Partial Differential Equations (PDEs) analytically using separation of variables and integral transforms, including Fourier and Laplace transforms.
- Numerically solve Initial Value Problems (IVPs) using Euler, and Runge-Kutta methods.
- Apply explicit and implicit Finite-Difference Methods (FDM) to solve combined IVPs and Boundary Value Problems (BVPs).
- Attain working knowledge of weighted residuals, and use the Finite-Element Methods (FEM) to solve PDEs relevant to mechanical engineering disciplines.
- Develop programming skills and algorithmic thinking necessary to model and solve advanced engineering mathematical problems.
- Troubleshoot written codes, validate numerical codes against analytical benchmarks, and analyze the results.

**MEGN503. GRADUATE SEMINAR. 0.0 Semester Hrs.**
This is a seminar forum for graduate students to present their research projects, critique others' presentations, understand the breadth of engineering projects both within their specialty area and across the Division, hear from leaders of industry about contemporary engineering as well as socio-economical and marketing issues facing today's competitive global environment. In order to improve communication skills, each student is required to present a seminar in this course before his/her graduation from the Mechanical Engineering graduate program. 1 hour per week; 0 semester hours. Course is repeatable, but no coursework credit is awarded. Prerequisites: Graduate standing.

**MEGN505. ADVANCED DYNAMICS. 3.0 Semester Hrs.**
This course will teach advanced methods for describing and analyzing equations of motion for mechanical systems. This class is intended for students who have a solid grasp of dynamics and differential equations. Course topics include: Lagrangian mechanics, Hamiltonian mechanics, constraints in mechanical systems, 3-D rigid body motion, stability and bifurcations of nonlinear systems, and dynamical systems theory. With these tools, students will have the capacity to model and analyze the dynamics of complex mechanical systems. The knowledge and skills from this class will help prepare students for potential careers in biomechanics, robotics, aerospace, and more.
**Course Learning Outcomes**

- 1. Analyze the kinematics of mechanical systems in both inertial and rotating reference frames using the vector differentiation formula.
- 2. Apply Lagrange's equations and Hamilton's equations to derive the equations of motion for mechanical systems.
- 3. Analyze mechanical systems with both holonomic and nonholonomic constraints using Lagrange's equations.
- 4. Evaluate the stability of equilibrium points in nonlinear ordinary differential equation models of dynamics.
- 5. Analyze bifurcations in ordinary differential equation models as parameters of the system are changed.
- 6. Analyze the dynamics of systems of rigid bodies in 3-dimensions.
- 7. Create models of the equations of motion of real-world mechanical systems using Newtonian, Lagrangian, or Hamiltonian mechanics.
- 8. Analyze the motion of mechanical systems and the impacts of parameters using numerical methods for ordinary differential equations.

**MEGN510. THEORY OF ELASTICITY. 3.0 Semester Hrs.**
This is a graduate course that builds upon your knowledge of Continuum Mechanics to develop an understanding of the Theory of Elasticity. Working individually and in small groups, we will review tensor analysis, develop the governing field equations, specify boundary conditions, and apply solution methods to solve linear elastic deformation problems. In addition, we will explore solutions for plane strain, plane stress, and non-

circular torsional examples. Students will prepare for future studies of non-linear elasticity, inelasticity, and fracture mechanics.
**Course Learning Outcomes**

- Apply the conventions of indicial notation, orthonormal basis transformation rules of tensors, dyadic representation of tensors, and eigenvalue problems of second-order tensors.
- Apply tensor algebra and calculus definitions in Cartesian, Cylindrical, and Spherical coordinates.
- Recognize the physical significance and geometric interpretation of the strain-displacement relations and compatibility equations. Calculate principal strains and the corresponding principal directions of strain, maximum longitudinal, and maximum shear strain.
- Calculate the strain state at a point by applying strain transformation equations to experimental data collected from strain gauges and rosettes.
- Calculate normal and shear tractions on planes of interest, projected shear traction, principal stresses and principal directions of stress.
- Formulate the field equations for linear isotropic elasticity and derive alternative forms for field equations.
- Apply the semi-inverse method and an Airy stress function to solve two-dimensional elasticity problems in plane strain and plane stress. Using numerical analysis software, plot the solutions and interpret the results and their significance.
- Apply the Prandtl stress function to solve torsional elasticity problems. Using numerical analysis software, plot the solutions and interpret the results and their significance.
- Apply conditions for material symmetry to develop the stiffness and compliance tensors for monoclinic, orthotropic, transversely isotropic, cubic, and isotropic materials.

**MEGN511. FATIGUE AND FRACTURE. 3.0 Semester Hrs.**
Equivalent with MTGN545,
Equivalent with MTGN545. This is a graduate level course in which students will learn basic fracture mechanics as applied to engineering materials. This course will cover crack growth and fracture mechanisms; cohesive strength concept; displacement, strain and stress fields in LEFM; stress intensity factors, stress concentrations, and strain energy release rate within LEFM; fracture toughness tests; plastic zone concepts; and fatigue life prediction.
**Course Learning Outcomes**

- Obtain and analyze case studies of fracture incidents to determine what caused the incident (comment on crack growth mechanism(s) and fracture mechanism) and make recommendations for how to prevent such an incident from happening again.
- Solve for and analyze the stress, strain and displacement fields for a general fracture mechanics problem in the linear elastic fracture (LEFM) regime
- Identify and formulate stress functions, stress intensity factors (SIFs) and strain energy release rates for general problems within the LEFM regime. Students will also be able to predict stress states and evaluate failure criteria using SIFs.
- Evaluate a fracture toughness test to judge if the test is valid using the most common ASTM testing standards (if they exist).
- Perform plastic zone correction analysis using simplified models.
- Apply simplified fatigue analysis to a specimen to estimate allowable stresses, evaluate possible fatigue damage and judge life expectancy prediction.
- Implement a simplified numerical model using software often used in industry, perform a delamination onset and growth experiment and analyze a composite specimen using two different crack advancing models.

**MEGN514. CONTINUUM MECHANICS. 3.0 Semester Hrs.**
This is a graduate course covering fundamentals of continuum mechanics and constitutive modeling. The goal of the course is to provide graduate students interested in fluid and solid mechanics with the foundation necessary to review and write papers in the field. Students will also gain experience interpreting, formulating, deriving, and implementing three-dimensional constitutive laws. The course explores six subjects: 1. Mathematical Preliminaries of Continuum Mechanics (Vectors, Tensors, Indicial Notation, Tensor Properties and Operations, Coordinate Transformations) 2. Stress (Traction, Invariants, Principal Values) 3. Motion and Deformation (Deformation Rates, Geometric Measures, Strain Tensors, Linearized Displacement Gradients) 4. Balance Laws (Conservation of Mass, Momentum, Energy) 5. Ideal Constitutive Relations (Frictionless & Linearly Viscous Fluids, Elasticity) 6. Constitutive Modeling (Formulation, Derivation, Implementation, Programming).
**Course Learning Outcomes**

- Students will learn vector calculus and index notation by solving problems sets and writing their own Matlab toolboxes of vector calculus operators.
- Students will learn general formulations of stress, strain, motion and balance laws by solving problem sets.
- Students will be introduced to constitutive modeling for both fluids and solids by solving problem sets and coding a model of their choice for the final project.

**MEGN515. COMPUTATIONAL MECHANICS. 3.0 Semester Hrs.**
A graduate course in computational mechanics with an emphasis on a studying the major numerical techniques used to solve problems that arise in mechanics and some related topical areas. Variational methods are applied throughout as a general approach in the development of many of these computational techniques. A wide range of problems are addressed in one- and two- dimensions which include linear and nonlinear elastic and elastoplastic steady state mechanics problems. Computational algorithms for time dependent problems such as transient dynamics and viscoplasticity are also addressed. In the latter part of the course an introduction to computational methods employing boundary integral equations, and particle methods for solving the mechanical behavior of multi-body systems are also given. Note all the software used in this course is written in MATLAB which has become a widely acceptable engineering programming tool. Prerequisite: MEGN502.
**Course Learning Outcomes**

- Understand and apply the variational approach to governing equations in the development of finite element algorithms.
- Develop, implement and apply computational algorithms to solve linear and nonlinear steady problems.
- Develop, implement and apply computational algorithms to solve transient problems.
- Perform extensive computer coding in MATLAB to develop and modify existing computational mechanics algorithms.

**MEGN517. NONLINEAR MATERIAL BEHAVIOR. 3.0 Semester Hrs.**
This course provides students with a foundational knowledge in the mechanics of solid materials displaying nonlinear deformation behavior. The course introduces general measures of deformation, such as

deformation tensors, velocity gradients, stretch rate and spin tensors, as well as measures of stress, including Cauchy, Green, nominal and material stress. These concepts create a foundation on which are built in-depth descriptions of hypoelastic, hyperelastic, and viscoelastic materials, as well as plastic and viscoplastic material behaviors. For each material behavior addressed, students will put relevant mechanics theory into practice by solving problems from contemporary applications (e.g., additive manufacturing, biomechanics, battery mechanics, aerospace). A working knowledge of continuum mechanics or elasticity theory would be helpful but is not required.

**Course Learning Outcomes**

- Explain and apply different measures of deformation, including displacement, different strain tensors, and corresponding compatibility equations.
- Explain, compare, and apply different stress tensors as well as different constitutive relationships between stress and strain tensors; analyze boundary conditions.
- Recall and apply different functional forms of the strain energy density, explain the differences between hypo and hyper-elastic stress-strain relations, and analyze the relevance of these materials in practical applications.
- Analyze the properties and deformation behaviors of polymers; calibrate or design the properties of polymers using scaling relationships.
- Explain and apply flow and hardening laws that govern the behavior of metals loaded beyond yield, and analyze incremental stress-strain relations and stability through the perspective of maximum plastic flow and Drucker's postulate,
- Analyze creep behavior and viscoplastic materials in the small and high strain rate regimes.

**MEGN523. APPLIED COMPUTATIONAL FLUID DYNAMICS. 3.0 Semester Hrs.**

The Applied Computational Fluid Dynamic course introduces the student to modeling and analysis of fluid mechanics problems via the finite difference and finite volume method. Fundamentals of CFD theory, solution, procedures, techniques, and analysis are discussed. Students will use ANSYS/Fluent CFD software to solve various fluid mechanics problems. Prerequisites: MEGN351.

**Course Learning Outcomes**

- The student will demonstrate the ability to use modern CFD software tools to create flow geometries, generate an adequate mesh to obtain an accurate solution, select appropriate solvers to obtain a flow solution, and visualize the resulting flow field.
- The student will replicate results from simple CFD models using fundamental numerical solutions through the governing fluid mechanics equations.
- The students will analyze a flow field to determine various quantities of interest, such as flow rates, heat fluxes, pressures, friction losses.
- The student will demonstrate the ability to recognize the type of fluid flow that is occurring in a particular physical system and to use the appropriate models/equations to investigate the flow.
- The student will design a complex (real) fluid-flow system, then using CFD solve for the flow, finally investigate the fluid-flow behavior, accuracy and explain the results.
- The student will demonstrate the ability to communicate the results, application and impact of typical CFD solutions to fluid-flow problems.

**MEGN527. VEHICLE DYNAMICS AND POWERTRAIN SYSTEMS. 3.0 Semester Hrs.**

This course offers an introduction to automotive engineering with a focus on vehicle design, suspension, powertrain and aerodynamics. The course is designed to introduce students to both theoretical and practical concepts of vehicle design with applications in increasing fuel efficiency and vehicle performance. The study of automotive engineering is of increasing importance as new technologies emerge and advances continue to be made to existing designs to create the ultimate driving experience; while having minimal impact on the environment by reducing tailpipe gas emissions, noise pollution, and waste material during manufacturing of new vehicles. Prerequisites: MEGN391.

**Course Learning Outcomes**

- Students will use fundamental lateral and longitudinal dynamic equations to design the proper suspension setup for various road and racing scenarios
- Students will be able to identify key components of a vehicle's suspension and powertrain system and describe their respective function to the performance of the vehicle
- Students will perform relevant calculations and numerical modeling related to vehicle design and handling characteristics (e.g. roll, over/under-steer)
- Students will be able to analyze the overall design of a vehicle's exterior to calculate the impact of drag and lift forces on vehicle performance as it relates to fuel efficiency and top speed.
- Students will solve basic engine performance calculations related to power and torque and determine which final drive ratio is adequate for certain racing applications

**MEGN532. EXPERIMENTAL METHODS IN BIOMECHANICS. 3.0 Semester Hrs.**

Introduction to experimental methods in biomechanical research. Topics include experimental design, hypothesis testing, motion capture, kinematic models, ground reaction force data collection, electromyography, inverse dynamics calculations, ethical conduct of human subjects research, and clinical and engineering applications. There is a strong emphasis on hands-on data collection and technical presentation of results. The course will culminate in individual projects combining multiple experimental measurement techniques. 3 hours lecture; 3.0 semester hours. Prerequisite: Graduate Student Standing.

**Course Learning Outcomes**

- Collect motion tracking, force and electromyographic data to answer biomechanical research questions.
- Process experimental data using appropriate filtering and normalization techniques.
- Analyze experimental data in biomechanics including kinematics, ground reaction forces, and electromyography.
- Interpret biomechanical data to apply results to physiological phenomena.

**MEGN535. MODELING AND SIMULATION OF HUMAN MOVEMENT. 3.0 Semester Hrs.**

Introduction to musculoskeletal modeling and simulation in movement biomechanics. The class includes a synthesis of musculoskeletal properties and interactions with the environment to construct detailed computer models and simulations. Topics include kinematic model definition, modeling nonlinear muscle properties, inverse dynamics, forward dynamics, movement optimization, and muscle recruitment solutions. The class culminates in final projects incorporating

musculoskeletal models, simulation development and computational analysis. This class requires a background in programming, dynamics, and an introduction to biomechanics. This is a graduate version of the undergraduate course MEGN 435; students may not take both MEGN 435 and MEGN 535. Prerequisite: MEGN315 and MEGN330.
**Course Learning Outcomes**

- Develop and implement musculoskeletal models using contemporary computational tools.
- Identify the assumptions, challenges, and opportunities in biomechanical modeling.
- Critically evaluate scholarly articles in biomechanical modeling and simulation literature.

**MEGN536. COMPUTATIONAL BIOMECHANICS. 3.0 Semester Hrs.**
Computational Biomechanics provides an introduction to the application of computer simulation to solve fundamental problems in biomechanics and bioengineering. Musculoskeletal biomechanics, joint kinematics, medical image reconstruction, hard and soft tissue modeling, and medical device design are considered in the context biomechanical investigations and analyses, culminating in a final design project which requires utilization of the tools and skills learned during the course to design and analyze an assistive device. Leading commercial software tools are introduced with hands-on exercises. An emphasis is placed on understanding the advantages and limitations of the computational tools and the need for rigorous verification and validation of all modeling tasks. Clinical application of biomechanical modeling tools is highlighted and impact on patient quality of life is discussed. Prerequisite: MEGN330, MEGN324.
**Course Learning Outcomes**

- Execute constrained optimization analyses in MATLAB to solve inverse kinematics, inverse dynamics, and muscle recruitment problems to calculate, predict, and analyze biomechanical quantities (e.g., joint kinematics and kinetics, muscle forces, and joint contact loads) during human motion.
- Apply musculoskeletal modeling software for verification, validation, and uncertainty quantification of biomechanics computations.
- Apply the v-diagram for medical device design control and explain the implementation of the engineering tasks embodied by this design paradigm.
- Apply computational biomechanics skills to design a medical device; analyze and justify the strengths and weaknesses of the design.

**MEGN540. MECHATRONICS. 3.0 Semester Hrs.**
A course focusing on implementation aspects of mechatronic and control systems. Significant lab component involving embedded C programming on a mechatronics teaching platform, called a haptic paddle, a single degree-of-freedom force-feedback joystick.
**Course Learning Outcomes**

- Become proficient in mechanical system modeling, system identification and simulations.
- Develop an understanding of how control theory is applied and implemented in practice.
- Learn fundamentals of and how to use semiconductor devices in mechatronic systems.
- Learn the basics of sensor and actuator theory, design, and application.
- Gain experience in embedded C programming for mechatronic systems.
- Gain experience in research article reading and technical presentations.

**MEGN544. ROBOT MECHANICS: KINEMATICS, DYNAMICS, AND CONTROL. 3.0 Semester Hrs.**
Mathematical representation of robot structures. Mechanical analysis including kinematics, dynamics, and design of robot manipulators. Representations for trajectories and path planning for robots. Fundamentals of robot control including, linear, nonlinear and force control methods. Introduction to off-line programming techniques and simulation. Robotics students should register for ROBO554. Prerequisite: EENG307 and MEGN441.
**Course Learning Outcomes**

- Understand fundamental concepts of robotics, including kinematics, dynamics and control theory for spatial motion.
- Analyze forward kinematics using Euler angles, angle-axis, and quaternion representation, compute inverse kinematics, and address kinematic singularities through constraint optimization.
- Design trajectory planning algorithms using splines and B-splines for smooth motion generation.
- Model robotic system dynamics using the Newton-Euler equations and compute inverse dynamics with recursive methods.
- Understand fundamental joint space control methodologies.
- Implement kinematics, dynamics, and control methodologies for robotic manipulators in simulation.

**MEGN545. ADVANCED ROBOT CONTROL. 3.0 Semester Hrs.**
The goal of this course is to give the students an introduction to a fundamental working knowledge of the main techniques of intelligent learning-based control and their applications in robotics and autonomous systems. Specific topics include neural network based control, model predictive control, reinforcement learning based control, fuzzy logic control, and human-in-the-loop control.
**Course Learning Outcomes**

- Obtain a basic understanding of a variety of intelligent control techniques and know how these techniques are applied to robotics engineering.
- Design robot control systems using neural network.
- Design robot control systems using reinforcement learning.
- Read and assess technical papers in intelligent robot control.
- Conduct class projects related to advanced robot control.

**MEGN551. ADVANCED FLUID MECHANICS. 3.0 Semester Hrs.**
This is a first-year graduate course that covers the fundamentals of incompressible fluid mechanics with a focus on differential analysis and building a foundation in the required concepts for subsequent study of computational fluid dynamics, turbulence, and compressible flow. We also explore the underlying mathematics of fluid mechanics and demonstrate how advanced mathematical tools can elucidate the real-world physics governing fluid flows. The course is divided into four parts covering (i) the governing equations of fluid mechanics, (ii) Stokes flows, (iii) ideal flows, and (iv) boundary layer flows.
**Course Learning Outcomes**

- Derive the conservation of mass and momentum equations in differential form.
- Physically describe the competing roles of pressure, viscosity, advection, and inertia and recognize how they are manifested in the governing equations and different flow regimes.

- Analyze fluid flows kinematically using flow lines and vorticity.
- Use order-of-magnitude analyses to simplify and solve partial differential equations.
- Identify and solve simple Stokes flows.
- Model two-dimensional potential flows.
- Derive the boundary layer equations and use them to model jets, wakes, and flat plates.

**MEGN552. FLUID, THERMAL, AND MASS TRANSPORT. 3.0 Semester Hrs.**
This course establishes the theoretical underpinnings of fluid mechanics, including fluid kinematics, stress-strain relationships, and derivation of the fluid-mechanical conservation equations. These include the mass-continuity and Navier-Stokes equations as well as the multi-component energy and species-conservation equations. Fluid-mechanical boundary-layer theory is developed and applied to situations arising in chemically reacting flow applications including combustion, chemical processing, and thin-film materials processing. 3 hours lecture; 3 semester hours. Prerequisite: MEGN451 or CBEN430.
**Course Learning Outcomes**

- Develop a fundamental and practical understanding of multi-component fluid flow.
- Derive and solve appropriate conservation equations.
- Learn computational methods to analyze multi-component and reacting flows
- Develop a sound engineering judgment for recognizing salient fluids characteristics.
- Identify and use dimensional or similarity reductions and generalizations.

**MEGN553. COMPUTATIONAL FLUID DYNAMICS. 3.0 Semester Hrs.**
Introduction to Computational Fluid Dynamics (CFD) for graduate students with no prior knowledge of this topic. Basic techniques for the numerical analysis of fluid flows. Acquisition of hands-on experience in the development of numerical algorithms and codes for the numerical modeling and simulation of flows and transport phenomena of practical and fundamental interest. Capabilities and limitations of CFD. Prerequisite: MEGN451.
**Course Learning Outcomes**

- Learn in-depth theoretical and mathematical development about the finite difference and finite volume methods for the numerical solution of the mass, momentum, energy, and species transport problems.
- Learn how to develop computer codes for solving the hyperbolic, parabolic, elliptic partial differential equations.
- Develop numerical codes for the solution of the 2D compressible Navier-Stokes equations.
- Learn how to validate and verify computer codes.
- Analyze and interpret the computed solutions of the governing conservation equations and to represent the computed numerical solution graphically using visualization techniques.
- Experience with the Ansys Fluent CFD code.

**MEGN554. ORBITAL MECHANICS. 3.0 Semester Hrs.**
Orbital Mechanics introduces students to the dynamics that govern motion of bodies in space and the utilization of these dynamics in spacecraft orbit and trajectory design. This course develops the mathematical foundation of propagating, describing, and manipulating the motion of a spacecraft in orbit. Throughout the semester students will script their own universe simulators to examine the various forces and geometries in orbit. Prerequisites: MEGN315.
**Course Learning Outcomes**

- 1. Calculate the position of a body (satellite) under Keplerian dynamics as a function of time.
- 2. Interpret the state and orbit type of a body (satellite) in an elliptical orbit using classic orbital elements.
- 3. Implement a state propagator for a body (satellite) in an elliptical orbit in Keplerian dynamics and under common perturbation models.
- 4. Calculate the impulsive delta-V maneuvers required to manipulate a body's (satellite) orbit state in common transfers
- 5. Have a basic understanding of the considerations taken when designing satellite orbits

**MEGN560. DESIGN AND SIMULATION OF THERMAL SYSTEMS. 3.0 Semester Hrs.**
In this course the principles of design, modeling, analysis, and optimization of processes, devices, and systems are introduced and applied to conventional and advanced energy conversion systems. It is intended to integrate conservation principles of thermodynamics (MEGN261) with the mechanism relations of fluid mechanics (MEGN351) and heat transfer (MEGN471). The course begins with general system design approaches and requirements and proceeds with mathematical modeling, simulation, analysis, and optimization methods. The design and simulation of energy systems is inherently computational and involves modeling of thermal equipment, system simulation using performance characteristics, thermodynamic properties, mechanistic relations, and optimization (typically with economic-based objective functions). Fundamental principles for steady-state and dynamic modeling are covered. Methods for system simulation which involves predicting performance with a given design (fixed geometry) are studied. Analysis methods that include Pinch Technology, Exergy Analysis, and Thermo-economics are examined and are considered complementary to achieving optimal designs. Optimization encompasses objective function formulation, systems analytical methods, and programming techniques. System optimization of the design and operating parameters of a configuration using various objective functions are explored through case studies and problem sets. Economics and optimization for analyses and design of advanced energy systems, such as Rankine and Brayton cycle power plants, combined.
**Course Learning Outcomes**

- Understand and distinguish between the various principles of design,modeling, analysis, and simulation as it applies to energy conversion systems.
- Be adept at integrating conservation principles of thermodynamics with mechanistic relations of fluid mechanics and heat transfer to predict the performance of energy conversion processes, devices, and systems.
- Understand the basic elements of techno-economic analysis and optimization-based design of thermal systems.
- Develop proficiency in the use of computational modeling, simulation, and optimization techniques to solve more realistic, complex problems in thermal systems.

**MEGN561. ADVANCED ENGINEERING THERMODYNAMICS. 3.0 Semester Hrs.**
First year graduate course in engineering thermodynamics that emphasizes a greater depth of study of undergraduate subject matter and an advancement to more complex analyses and topics. The

course begins with fundamental concepts, 1st and 2nd Law analyses of processes, devices, and systems and advances to equations of state, property relations, ideal and non-ideal gas mixtures, chemically reacting systems, and phase equilibrium. Historical and modern contexts on the development and advancements of thermodynamic concepts are given. Fundamental concepts are explored through the analysis of advanced thermodynamic phenomena and use of computational tools to solve more realistic problems. Prerequisite: MEGN261, MEGN351, MEGN471.
**Course Learning Outcomes**

- Understand the fundamental theory of the 1st and 2nd Laws of Thermodynamics.
- Recognize critical assumptions, property relations, and approaches for different physical situations.
- Understand how thermodynamic problems are solved and solve them using available computational tools and techniques.
- Use engineering thermodynamics in their research work or applications.

**MEGN565. ELECTRIC VEHICLE POWERTRAIN SYSTEMS. 3.0 Semester Hrs.**
In the fast-evolving world of sustainable transportation, it is essential for engineers in the automotive industry to understand energy conversion, storage, utilization, and optimization of vehicle powertrains. Electric Vehicle Powertrain Systems (EVPS) is designed to provide students with a comprehensive understanding of the essential powertrain components in battery-electric vehicles (BEVs) including motors, controllers, and battery packs. Through a combination of theoretical modeling and hands-on projects, students will gain knowledge and skills in powertrain system design to achieve vehicle objectives, encompassing energy analysis, power requirements, and efficiency considerations. The course will also explore the state-of-the-art in safety measures, management strategies, control systems, charging/balancing techniques, and State of Charge (SOC)/State of Health (SOH) estimation for EV battery packs. Prerequisites: MEGN 300 or EENG282.
**Course Learning Outcomes**

- Articulate the functions and interrelationships of the core powertrain components in electric vehicles, including the motor, controller, and battery pack
- Design a vehicle powertrain architecture and select powertrain components that meet the overarching goals of an electric vehicle, incorporating top-level requirements such as energy use, power output, and efficiency optimization
- Implement the Road Load Equation on dynamic course profiles to determine vehicle, battery, motor, and controller power and system energy requirements
- Explain the operating principles and fundamental characteristics of Li-ion batteries using underlying electrochemical processes and implement them in an equivalent circuit battery model
- Apply experimental methods used to characterize the performance of Li-ion cells in automotive applications, while elucidating the principles and significance of these techniques in assessing battery behavior and performance.
- Critically assess and compare the state of the art in safety protocols, management strategies, control systems, and charging/balancing techniques for battery packs in electric vehicle powertrain systems.
- Devise a functional design for a battery pack tailored to the specific requirements and constraints of a full-size electric vehicle, integrating considerations such as energy storage capacity, thermal management, safety measures, and space utilization
- Describe the basic operating principles of EV motors and controllers
- Explain the fundamentals and applications of Field Oriented Control in an EV powertrain
- Calculate vehicle performance characteristics based on operating limits of the full BEV architecture, including the batteries, motor, and controller

**MEGN566. COMBUSTION. 3.0 Semester Hrs.**
(I) An introduction to combustion. Course subjects include: the development of the Chapman-Jouget solutions for deflagration and detonation, a brief review of the fundamentals of kinetics and thermochemistry, development of solutions for diffusion flames and premixed flames, discussion of flame structure, pollutant formation, and combustion in practical systems. Prerequisite: MEGN451 or CBEN430. 3 hours lecture; 3 semester hours.

**MEGN567. PRINCIPLES OF BUILDING SCIENCE. 3.0 Semester Hrs.**
First or second year graduate course that covers the fundamentals of building energy systems, moist air processes, heating, ventilation, and air conditioning (HVAC) systems and the use of numerical models for heat and mass transfer to analyze advanced building technologies such as phase change materials, green roofs or cross laminated timber. This is a graduate version of the undergraduate course MEGN 467; students may not take both MEGN 467 and MEGN 567. Prerequisites: MEGN261, MEGN351, MEGN471.
**Course Learning Outcomes**

- Understand and apply fundamental principles to HVAC design.
- Describe components in HVAC systems.
- Understand how building HVAC loads are calculated and calculate building HVAC loads.
- Analyze advance building technologies using building energy simulations tools.
- Write technical report based on energy modeling results.

**MEGN569. FUEL CELL SCIENCE AND TECHNOLOGY. 3.0 Semester Hrs.**
Equivalent with CBEN569,CHEN569,MLGN569,MTGN569,
Equivalent with CBEN569, CHEN569, MLGN569, MTGN569. Investigate fundamentals of fuel-cell operation and electrochemistry from a chemical-thermodynamics and materials- science perspective. Review types of fuel cells, fuel-processing requirements and approaches, and fuel-cell system integration. Examine current topics in fuel-cell science and technology. Fabricate and test operational fuel cells in the Colorado Fuel Cell Center. This is a graduate version of the undergraduate course MEGN469; students may not take both MEGN469 and MEGN569.
**Course Learning Outcomes**

- Contrast the advantages and disadvantages of fuel cells to other energy conversion technologies.
- Describe the basic mechanisms of fuel cell reactions, electron transfer, and ionic transport at the molecular scale.
- Calculate the ideal fuel cell voltage and efficiency as a function of gas concentrations, pressure, and temperature. Derive equations for activation, IR, and concentration losses in fuel cell systems.
- Identify the most significant kinetic constraints that limit current fuel cell performance and suggest research directions to improve performance. Describe and compare the major strategies for fuel cell stacking.
- Describe and compare the major strategies for fuel cell stacking.

- Describe and discuss the ancillary equipment necessary for a complete fuel-cell system, including fuel reforming and thermal management.
- Examine approaches to system modeling to identify system limitations and integration needs.
- Use numerical simulations to explore the interrelation between fuel cell system design, operating conditions, and performance/efficiency.

**MEGN570. ELECTROCHEMICAL SYSTEMS ENGINEERING. 3.0 Semester Hrs.**
In this course, students will gain fundamental, quantitative insight into the operation of electrochemical devices for engineering analysis across a range of length scales and applications. The course will use the development of numerical models as a lens through which to view electrochemical devices. However, the course will also deal extensively with "real world" systems and issues, including experimental characterization, system optimization and design, and the cyclical interplay between models and physical systems. The course begins by establishing the equations that govern device performance at the most fundamental level, describing chemical and electrochemical reactions, heat transfer, transport of charged and neutral species, and material properties in operating devices. Subsequently, these equations will be used to discuss and analyze engineering issues facing three basic types of electrochemical devices: fuel cells, batteries, and sensors. At each juncture will evaluate our equations to determine when simpler models may be more suitable. Throughout the semester, concepts will be applied in homework assignments, including an over-arching, semester-long project to build detailed numerical models for an application of each student's choosing.
**Course Learning Outcomes**

- Apply conservation of mass, species and energy to model electrochemical processes and predict performance.
- Use numerical simulations to design and optimize electrochemical systems.
- Given multiple alternatives, students will choose an appropriate level of detail for charge transfer and mass transport models.
- Interpret model simulation results to identify limiting physical processes in a given electrochemical device.

**MEGN571. ADVANCED HEAT TRANSFER. 3.0 Semester Hrs.**
This course provides students with the foundational knowledge and skills to use analytical and numerical approaches to solve interesting problems for design and performance analysis of materials, devices, and systems that involve heat transfer. The topics include steady-state and transient conduction, boundary layer convection heat transfer, and gray body radiative surface exchange. The knowledge of these topics and the mathematical and numerical skills are combined in various multi-mode heat transfer problems related to an array of industries such as sustainable energy conversion, aerospace, and/or manufacturing and materials processing, electronics packaging, and building design and analysis. A final course project gives students the opportunity to utilize the skills gained in this course in a team design project.
**Course Learning Outcomes**

- Apply energy balances to control volumes/surfaces to derive and solve differential equations for steady and transient temperatures and heat fluxes within an object and at boundary interfaces.
- Develop reduced order models of internal and external flows using appropriate heat transfer correlations with or without turbulence, phase change, or buoyancy to predict profiles of temperature and heat fluxes.
- Calculate surface radiative properties, evaluate view factors, and solve numerically radiation exchange between surfaces.
- Identify and implement reduced-order models of heat exchangers and other thermal systems to estimate performance and complete design studies.
- Implement computational models of multi-modal heat transfer within thermal devices, including solution of coupled differential equations and non-linear systems of equations.

**MEGN579. OPTIMIZATION MODELS IN MANUFACTURING. 3.0 Semester Hrs.**
This course addresses the mathematical formulation and solution of optimization models relevant in manufacturing operations. The types of optimization models examined include: (i) network models; (ii) linear programs; (iii) integer programs; and (iv) nonlinear programs. Application areas include scheduling, blending, design, equipment replacement, logistics and transportation, among other topics. Students learn not only how to mathematically formulate the models, but also how to solve them with a state-of-the-art modeling language (AMPL) and appropriate solver (e.g. CPLEX or Minos). Algorithms for each problem class will be briefly discussed. This is a graduate version of the undergraduate course MEGN 479; students may not take both MEGN 479 and MEGN 579.
**Course Learning Outcomes**

- Understand the concept of optimization.
- Understand how optimization can be applied in a manufacturing setting.
- Differentiate between network models, linear programs, integer programs, and nonlinear programs.
- Be able to algebraically represent each type of optimization model.
- Implement optimization formulations in an algebraic modeling language and solve to obtain and analyze solutions.

**MEGN585. NETWORK MODELS. 3.0 Semester Hrs.**
We examine network flow models that arise in manufacturing, energy, mining, transportation and logistics: minimum cost flow models in transportation, shortest path problems in assigning inspection effort on a manufacturing line, and maximum flow models to allocate machine-hours to jobs. We also discuss an algorithm or two applicable to each problem class. Computer use for modeling (in a language such as AMPL) and solving (with software such as CPLEX) these optimization problems is introduced. Offered every other year. This is a graduate version of the undergraduate course MEGN 485; students may not take both MEGN485 and MEGN 585.
**Course Learning Outcomes**

- Understand how to differentiate spanning tree, shortest path, maximum flow and minimum cost flow models.
- Understand how to graphically depict and mathematically model spanning tree, shortest path, maximum flow and minimum cost flow models.
- Understand algorithms that solve model spanning tree, shortest path, maximum flow and minimum cost flow models.
- Understand the difference between network and non-network optimization models

**MEGN586. LINEAR OPTIMIZATION. 3.0 Semester Hrs.**
We address the formulation of linear programming models, linear programs in two dimensions, standard form, the Simplex method, duality

theory, complementary slackness conditions, sensitivity analysis, and multi-objective programming. Applications of linear programming models include, but are not limited to, the areas of manufacturing, energy, mining, transportation and logistics, and the military. Computer use for modeling (in a language such as AMPL) and solving (with software such as CPLEX) these optimization problems is introduced. This is a graduate version of the undergraduate course MEGN 486; students may not take both MEGN 486 and MEGN 586.

**Course Learning Outcomes**

- Understand how to formulate linear optimization models.
- Understand how to solve linear optimization models, both by hand and with the computer through an algebraic modeling language and a state-of-the-art solver.
- Understand the special structure underlying linear optimization models and how this affects their ability to be solved.
- Understand sensitivity and post-optimality analysis.

**MEGN587. NONLINEAR OPTIMIZATION. 3.0 Semester Hrs.**

Equivalent with MEGN487,

This course addresses both unconstrained and constrained nonlinear model formulation and corresponding algorithms (e.g., Gradient Search and Newton's Method, and Lagrange Multiplier Methods and Reduced Gradient Algorithms, respectively). Applications of state-of-the-art hardware and software will emphasize solving real-world engineering problems in areas such as manufacturing, energy, mining, transportation and logistics, and the military. Computer use for modeling (in a language such as AMPL) and solving (with an algorithm such as MINOS) these optimization problems is introduced. Offered every other year. Prerequisite: MATH111.

**Course Learning Outcomes**

- Understand how to formulate nonlinear optimization models.
- Understand how to solve nonlinear optimization models, both by hand and with the computer through an algebraic modeling language and a state-of-the-art solver.
- Understand the special structure underlying nonlinear optimization models and how this affects their ability to be solved.

**MEGN588. INTEGER OPTIMIZATION. 3.0 Semester Hrs.**

Equivalent with MEGN488,

(I) This course addresses the formulation of integer programming models, the branch-and-bound algorithm, total unimodularity and the ease with which these models are solved, and then suggest methods to increase tractability, including cuts, strong formulations, and decomposition techniques, e.g., Lagrangian relaxation, Benders decomposition. Applications include manufacturing, energy, mining, transportation and logistics, and the military. Computer use for modeling (in a language such as AMPL) and solving (with software such as CPLEX) these optimization problems is introduced. Offered every other year. 3 hours lecture; 3 semester hours. Prerequisite: MATH111.

**Course Learning Outcomes**

- Understand how to formulate linear-integer optimization models.
- Understand how to solve linear-integer optimization models, both by hand and with the computer through an algebraic modeling language and a state-of-the-art solver.
- Understand the special structure underlying linear-integer optimization models and how this affects their ability to be solved.
- Understand decomposition techniques to aid in solution.

**MEGN592. RISK AND RELIABILITY ENGINEERING ANALYSIS AND DESIGN. 3.0 Semester Hrs.**

The importance of understanding, assessing, communicating, and making decisions based in part upon risk, reliability, robustness, and uncertainty is rapidly increasing in a variety of industries (e.g.: petroleum, electric power production, etc.) and has been a focus of some industries for many decades (e.g.: nuclear power, aerospace, automotive, etc). This graduate class will provide the student with a technical understanding of and ability to use common risk assessment tools such as Reliability Block Diagrams (RBD), Failure Modes and Effects Analysis (FMEA), and Probabilistic Risk Assessment (PRA); and new tools being developed in universities including Function Failure Design Methods (FFDM), Function Failure Identification and Propagation (FFIP), and Uncoupled Failure Flow State Reasoning (UFFSR) among others. Students will also be provided with a high-level overview of what risk really means and how to contextualize risk information. Methods of communicating and making decisions based in part upon risk.

**Course Learning Outcomes**

- Understand and be able to use probability statistics.
- Understand and be able to use Bayesian statistical methods.
- Demonstrate ability to use PRA software.
- Demonstrate ability to model a complex engineered system using several (RBD, FMEA, PRA, FFDM, etc) risk and reliability methods.

**MEGN598. SPECIAL TOPICS IN MECHANICAL ENGINEERING. 0-6 Semester Hr.**

Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**MEGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**MEGN651. ADVANCED COMPUTATIONAL FLUID DYNAMICS. 3.0 Semester Hrs.**

This course covers the fundamentals of computational fluid dynamics (CFD) for unsteady incompressible fluids flows, including examples of heat and mass transport. The course focuses on finite volume-methods, efficient projection methods for simulating unsteady flows, and recent advances in immersed boundary methods for complicated geometries. The course is entirely based on weekly homework, through which students learn how to build and benchmark their own CFD codes. By the end of the course, students should have the required fundamentals to either build their own research codes or use commercial and open source CFD codes intelligently. Prerequisites: MEGN502 and MEGN551 are recommended.

**Course Learning Outcomes**

- Develop an in-house CFD code that simulates unsteady incompressible fluid flows with heat and mass transport.
- Verify the spatial and temporal accuracy of CFD codes.
- Explain how the competing roles of advection and diffusion impact CFD.
- Explain how the role of pressure in incompressible flows impacts CFD.

- Model flow over a complex surface using an immersed boundary method.

**MEGN686. ADVANCED LINEAR OPTIMIZATION. 3.0 Semester Hrs.**
As an advanced course in optimization, we expand upon topics in linear programming: advanced formulation, the dual simplex method, the interior point method, algorithmic tuning for linear programs (including numerical stability considerations), column generation, and Dantzig-Wolfe decomposition. Time permitting, dynamic programming is introduced. Applications of state-of-the-art hardware and software emphasize solving real-world problems in areas such as manufacturing, mining, energy, transportation and logistics, and the military. Computers are used for model formulation and solution. Prerequisite: MEGN586.
**Course Learning Outcomes**

- Understand how to formulate complicated linear optimization models.
- Dual Simplex Method and Interior Point Method.
- Algorithmic Tuning.
- Column Generation and Dantzig-Wolfe Decomposition.

**MEGN688. ADVANCED INTEGER OPTIMIZATION. 3.0 Semester Hrs.**
As an advanced course in optimization, we expand upon topics in integer programming: advanced formulation, strong integer programming formulations (e.g., symmetry elimination, variable elimination, persistence), in-depth mixed integer programming cuts, rounding heuristics, constraint programming, and decompositions. Applications of state-of-the-art hardware and software emphasize solving real-world problems in areas such as manufacturing, mining, energy, transportation and logistics, and the military. Computers are used for model formulation and solution. Prerequisite: MEGN588.
**Course Learning Outcomes**

- Know how to formulate advanced integer optimization models 2. Be familiar with advanced algorithms to solve these models 3. Be able to use software, including scripting, to model and solve these models 4. Understand the theory behind and mathematical tenants of advanced integer optimization models.
- Be familiar with advanced algorithms to solve these models.
- Use software, including scripting, to model and solve these models.
- Understand the theory behind and mathematical tenants of advanced integer optimization models.

**MEGN698. SPECIAL TOPICS. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**MEGN699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**MEGN707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.**
Research credit hours required for completion of a Masters-level thesis or Doctoral dissertation. Research must be carried out under the direct supervision of the student's faculty advisor. Variable class and semester hours. Repeatable for credit.

## Professor and Department Head

Anthony J. Petrella, Department Head

## Professors

Alexandra Newman, Director of Operations Research with Engineering Program

Carl Frick, Professor and Dean of Graduate Studies

Cristian Ciobanu

Gregory Jackson

John Berger, Dean of Energy and Materials

Mohsen Asle Zaeem

Neal Sullivan

Robert Braun, University Distinguished Professor of Mechanical Engineering and Director of Mines/NREL Advanced Energy Systems Program

Robert Kee, George R. Brown Distinguished Professor

## Associate Professors

Andrew Petruska

Anne Silverman

Anthony J. Petrella, Interim Department Head

Joy Gockel

Leslie Lamberson

Mark Deinert

Nils Tilton

Owen Hildreth

Paulo Cesar Tabares-Velasco

Ruichong "Ray" Zhang

Steven DeCaluwe, Director of Graduate Studies

Veronica Eliasson

Xiaoli Zhang

## Assistant Professors

Aashutosh Mistry

Andrew Osborne

Denis Aslangil

Rajavasanth Rajasegar

Samantha "Sam" Webster

Frankie Zhu

### Professors of Practice

Angel Abbud-Madrid, Director of Space Resources Program

Brian Gockel

Christopher Dreyer

Craig Brice, Director of Additive Manufacturing Program

George Sowers

### Teaching Professors

Derrick Rodriguez

Kristine R. Csavina, Director of Capstone

Ventzi Karaivanov

### Teaching Associate Professors

Daniel Blood, Director of Undergraduate Studies

Jeffrey Ackerman

Jeffrey Wheeler

Oyvind Nilsen

### Teaching Assistant Professors

Adam Duran

Elijah Kuska

Gary Nave

Jim Wong

Kelly Rickey

Mathew Johnson

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Siby Thomas

Stephen Geer

### Affiliate Professor of Mechanical Engineering

Mike Mooney

### Research Associate Professors

Sandrine Ricote

Huayang Zhu

### Research Assistant Professors

Omid Babaie-Rizvandi

Carolina Herradon Hernandez

Garrison Hommer

### Research Professor

Brian Thomas

### Emeriti Professors

Joan Gosink

Graham Mustoe

Robert King

Terry Parker

### Emeriti Associate Professors

Dave Munoz

Joel Bach

John P.H. Steele

# Metallurgical and Materials Engineering

## Degrees Offered

- Master of Engineering (Metallurgical and Materials Engineering)
- Master of Science (Metallurgical and Materials Engineering)
- Doctor of Philosophy (Metallurgical and Materials Engineering)

## Program Description

The program of study for the Master or Doctor of Philosophy degrees in Metallurgical and Materials Engineering is selected by the student in consultation with her or his advisor, and with the approval of the thesis committee. The program can be tailored within the framework of the regulations of the Graduate School to match the student's interests while maintaining the main theme of materials engineering and processing. There are three areas of specialization within the department:

- Physical and Mechanical Metallurgy
- Physicochemical Processing of Materials
- Ceramic Engineering

The Department is home to four research centers:

- Advanced Steel Processing and Products Research Center (ASPPRC)
- Center for Advanced Non Ferrous Structural Alloys (CANFSA)
- Center for Welding Joining, and Coatings Research (CWJCR)
- Colorado Center for Advanced Ceramics (CCAC)

The Kroll Institute for Extractive Metallurgy (KIEM) and Nuclear Science and Engineering Center (NuSEC) research centers also operate closely with the department.

## Degree Program Requirements

The program requirements for the three graduate degrees offered by the department are listed below:

## Master of Engineering Degree

Requirements: A **minimum total of 30 credits** consisting of:

| Coursework | Credits | |
|---|---|---|
| Approved Coursework* | 18.0 - 26.0 | |
| MTGN501 | MME GRADUATE SEMINAR ** | 1.0 |
| MTGN700 | GRADUATE RESEARCH CREDIT: MASTER OF ENGINEERING (or designated design course) *** | 3.0-5.0 |

* 18 of the 26 credits must be taken from the Metallurgy or Materials Science courses. All other course credits can be taken in any department.

** Students are expected to enroll in this seminar every semester, but a maximum of 1 credit may apply toward the degree.

*** Students can choose to fulfill the NT master's degree requirements by either taking 30 credits, including 3 hours of a design course, or with advisor approval, take 25 hours of course credits and have 5 hours devoted to a project; in that case, students will have to defend an engineering report to a three-person committee.

**Designated Design courses include:**

| | | |
|---|---|---|
| MTGN549 | CURRENT DEVELOPMENTS IN FERROUS ALLOYS | 3.0 |
| MTGN564 | ADVANCED FORGING AND FORMING | 3.0 |
| MTGN560 | ANALYSIS OF METALLURGICAL FAILURES | 3.0 |
| MTGN598 | MECHANICAL PROPERTIES OF MATERIALS | 3.0 |
| MTGN598 | ELECTRON MICROSCOPY | 3.0 |
| Alternative courses can be substituted with approval from the advisor and department head | | |

**Restrictions:**

1. Only 3 credits of independent coursework, e.g., MTGN599, may be applied toward the degree.
2. Courses taken to remove deficiencies may not be applied toward the degree.

The Master of Engineering Degree can also be obtained as part of the combined undergraduate/graduate degree program.

## Master of Science Degree

Requirements: A **minimum total of 30 credits** consisting of:

| Coursework | Credits | |
|---|---|---|
| Approved Coursework* | 18.0 - 23.0 | |
| MTGN501 | MME GRADUATE SEMINAR ** | 1.0 |
| MTGN707 | GRADUATE THESIS / DISSERTATION RESEARCH CREDIT *** | 6.0-11.0 |

* Minimum of 18 credits of approved coursework is required. 12 credits must be taken from the Metallurgy or Materials Science courses. All other course credits can be taken in any department.

** Students are expected to enroll in this seminar every semester, but a maximum of 1 credit may apply toward the degree.

*** 6 to 11 research credits, to include MTGN707.

**Restrictions:**

1. Only 3 credits of independent coursework, e.g., MTGN599, may be applied toward the degree.
2. Courses taken to remove deficiencies may not be applied toward the degree.

**Additional Degree Requirements:**

1. Approval of all courses by the thesis committee and the department head. (thesis committee: consisting of three or more members, including the advisor and at least one additional member from the Metallurgical and Materials Engineering Department.)
2. Submittal and successful oral defense of a thesis before a thesis committee. The thesis must present the results of original scientific research or development.

The Master of Science Degree can also be obtained as part of the combined undergraduate/graduate degree program.

## Doctor of Philosophy Degree

Requirements: A **minimum total of 72 credits** consisting of:

| Coursework | Credits | |
|---|---|---|
| Approved Coursework* | 36.0 - 48.0 | |
| MTGN501 | MME GRADUATE SEMINAR ** | 1.0 |
| MTGN707 | GRADUATE THESIS / DISSERTATION RESEARCH CREDIT *** | 24.0-36.0 |

* A minimum of 36 credits of approved coursework, 24 of which must be in MTGN or MLGN. Credits previously earned for a master's degree may be applied, subject to approval, toward the doctoral degree provided that the master's degree was in Metallurgical and Materials Engineering or a similar field. At least 21 credits of approved coursework must be taken at Colorado School of Mines.
All courses and any applicable master's degree credits must be approved by the thesis committee and the department head (thesis committee consisting of: four or more members, including the advisor, at least two additional members from the Metallurgical and Materials Engineering Department, and at least one member from outside the Department.)

** Students are expected to enroll in this seminar every semester, but a maximum of 1 credit hour may apply toward the degree.

*** A minimum of 24 research credit hours, to include MTGN707.

**Restrictions:**

1. Only 6 credits of independent coursework, e.g., MTGN599, may be applied toward the degree.
2. Courses taken to remove deficiencies may not be applied toward the degree.

**Additional Degree Requirements:**

1. Presentation of a proposal on the thesis-research project to the thesis committee.
2. A passing grade on the written and oral Qualifying-Process (QP) Examinations.
3. Presentation of a Progress Report on their Research Project to the thesis committee is strongly recommended; this presentation is usually 6 months after successfully completing the QP Examinations and no fewer than six weeks before the defense of thesis.

4. Submittal and successful oral defense of a thesis before the thesis committee. The thesis must present the results of original scientific research or development.

## Prerequisites

The entering graduate student in the Department of Metallurgical and Materials Engineering must have completed an undergraduate program equivalent to that required for the BS degree in: Metallurgical and Materials Engineering, Materials Science, or a related field. This undergraduate program should have included a background in science fundamentals and engineering principles. A student who possesses this background but has not taken specific undergraduate courses in Metallurgical and Materials Engineering will be allowed to rectify these course deficiencies at the beginning of their program of study.

## Mines' Combined Undergraduate/Graduate Degree Program for Non-Thesis MS and Thesis-Based MS and PhD

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

## Fields of Research

## Ceramic Research

- Ceramic processing
- Ceramic-metal composites
- Functional materials
- Ion implantation
- Modeling of ceramic processing
- Solid oxide fuel cell materials and membranes
- Transparent conducting oxides

## Coatings Research

- Chemical vapor deposition
- Coating materials, films and applications
- Epitaxial growth
- Interfacial science
- Physical vapor deposition
- Surface mechanics
- Surface physics
- Tribology of thin films and coatings

## Extractive and Mineral Processing Research

- Chemical and physical processing of materials
- Electrometallurgy
- Hydrometallurgy
- Mineral processing
- Pyrometallurgy
- Recycling and recovery of materials
- Thermal plasma processing

## Nonferrous Research

- Aluminum alloys
- High entropy alloys
- Magnesium alloys
- Nonferrous structural alloys
- Shape memory alloys
- Superalloys
- Titanium alloys

## Polymers and Biomaterials Research

- Advanced polymer membranes and thin films
- Biopolymers
- Bio-mimetic and bio-inspired materials engineering
- Calcium phosphate-based ceramics
- Drug delivery
- Failure of medical devices
- Interfaces between materials and tissue
- Living/controlled polymerization
- Organic-inorganic hybrid materials
- Porous structured materials
- Self- and directed-assembly
- Structural medical alloys
- Tissue as a composite material

## Steel Research

- Advanced high strength steels
- Advanced steel coatings
- Carburized steels
- Deformation behavior of steels
- Fatigue behavior of steels
- Microalloyed steels
- Nickel-based steels
- Quench and partitioned steels
- Plate steels
- Sheet steels

## Welding and Joining Research

- Brazing of ultra wide gaps
- Explosive processing of materials
- Laser welding and processing
- Levitation for kinetics and surface tension evaluation
- Materials joining processes
- Pyrochemical kinetics studies using levitation
- Underwater and under oil welding
- Welding and joining science
- Welding rod development
- Welding stress management
- Weld metallurgy
- Weld wire development

## Nuclear Materials Research

- Nuclear materials characterization
- Nuclear materials processing
- Nuclear materials properties

## Experimental Methods

- 3D atom probe tomography
- Atomic force microscopy
- Computer modeling and simulation
- Electron microscopy
- Mathematical modeling of material processes
- Nanoindentation
- Nondestructive evaluation
- X-ray diffraction

## Other Research Areas

- Combustion synthesis
- Corrosion science and engineering
- Failure analysis
- Mechanical metallurgy
- Phase transformation and mechanism of microstructural change
- Physical metallurgy
- Reactive metals properties
- Strengthening mechanisms
- Structure-property relationships

## Courses

**MTGN501. MME GRADUATE SEMINAR. 0.5 Semester Hrs.**
(I, II) All full-time MME graduate students must attend the Metallurgical and Materials Engineering seminar. Students must take the Graduate Seminar course every semester that they are enrolled at CSM. At the end of each semester, students are assigned either a satisfactory or unsatisfactory progress grade, based on attendance, until the final semester of the student's degree program, when a letter grade is assigned based on all prior semesters' attendance grades. As a result, while these courses are taken each year, only a maximum of 1.0 hours total of course credit is conferred. Students who have official part-time status are not required to sign up for Graduate Seminar. Attendance of other seminars outside MME can substitute for seminar attendance in MME following course instructor approval. 1 hour lecture; 0.5 hours. Repeatable up to 1 hour.
**Course Learning Outcomes**

- Students will develop an appreciation for the diversity of research and research methods in materials science and engineering.

**MTGN505. MECHANICAL PROPERTIES OF MATERIALS. 3.0 Semester Hrs.**
Mechanical properties and relationships. Plastic deformation of crystalline materials. Relationships of microstructures to mechanical strength. Fracture, creep, and fatigue. Corequisites: MTGN445L.
**Course Learning Outcomes**

- Apply materials and mechanical fundamental principles of elastic and plastic deformation behavior to describe and interpret stress-strain behavior and strengthening mechanisms in solids
- Interpret and predict fracture and fatigue behavior of materials
- Reduce, interpret, and analyze experimental data from a variety of mechanical property tests
- Prepare and submit concise and coherent technical laboratory reports

**MTGN510. THERMAL PROPERTIES OF CERAMICS. 3.0 Semester Hrs.**
This course covers the fundamentals and applications of ceramic materials' responses to thermal energy. Thermal responses are fundamentally borne from atomic scale processes which will be covered in detail. Particular attention is paid to thermal conduction, melting, thermally induced strain, thermomechanical stresses, and engineering microstructures to obtain specific thermal performances. Prerequisite: MTGN315, MTGN310.
**Course Learning Outcomes**

- Same as existing MTGN410 course syllabus.

**MTGN511. SPECIAL METALLURGICAL AND MATERIALS ENGINEERING PROBLEMS. 1-3 Semester Hr.**
(I) Independent advanced work, not leading to a thesis. This may take the form of conferences, library, and laboratory work. Selection of assignment is arranged between student and a specific Department faculty-member. Prerequisite: Selection of topic. 1 to 3 semester hours. Repeatable for credit under different titles.

**MTGN512. SPECIAL METALLURGICAL AND MATERIALS ENGINEERING PROBLEMS. 1-3 Semester Hr.**
(II) Continuation of MTGN511. Prerequisite: Selection of topic. 1 to 3 semester hours. Repeatable for credit under different titles.

**MTGN523. APPLIED SURFACE AND SOLUTION CHEMISTRY. 3.0 Semester Hrs.**
(II) Solution and surface chemistry of importance in mineral and metallurgical operations. Prerequisite: none. 3 hours lecture; 3 semester hours. (Spring of odd years only.).

**MTGN526. GEL SCIENCE AND TECHNOLOGY. 3.0 Semester Hrs.**
An introduction to the science and technology of particulate and polymeric gels, emphasizing inorganic systems. Interparticle forces. Aggregation, network formation, percolation, and the gel transition. Gel structure, rheology, and mechanical properties. Application to solid-liquid separation operations (filtration, centrifugation, sedimentation) and to ceramics processing. Prerequisite: Graduate Status. 3 hours lecture; 3 semester hours. (Spring of odd
years only.).

**MTGN527. SOLID WASTE MINIMIZATION AND RECYCLING. 3.0 Semester Hrs.**
(II) Industrial case-studies, on the application of engineering principles to minimize waste formation and to meet solid waste recycling challenges. Proven and emerging solutions to solid waste environmental problems, especially those associated with metals. Prerequisites: ESGN500 and ESGN504. 3 hours lecture; 3 semester hours.

**MTGN528. EXTRACTIVE METALLURGY OF COPPER, GOLD AND SILVER. 3.0 Semester Hrs.**
Practical applications of fundamentals of chemical-processing-of-materials to the extraction of gold, silver and copper. Topics covered include: History; Ore deposits and mineralogy; Process Selection; Hydrometallurgy and leaching; Oxidation pretreatment; Purification and recovery; Refinement; Waste treatment; and Industrial examples. Prerequisites: Graduate or Senior in good-standing. 3 hours lecture, 3 semester hours.

**MTGN529. METALLURGICAL ENVIRONMENT. 3.0 Semester Hrs.**
(I) Effluents, wastes, and their point sources associated with metallurgical processes, such as mineral concentration and values extraction—providing for an interface between metallurgical process engineering and the environmental engineering areas. Fundamentals of metallurgical unit operations and unit processes, applied to waste and effluents control, recycling, and waste disposal. Examples which incorporate engineering design and cost components are included. Prerequisites: MTGN334. 3 hours lecture; 3 semester hours.

**MTGN530. ADVANCED IRON AND STEELMAKING. 3.0 Semester Hrs.**
(I) Physicochemical principles of gas-slag-metal reactions applied to the reduction of iron ore concentrates and to the refining of liquid iron to steel. The role of these reactions in reactor design—blast furnace and direct iron smelting furnace, pneumatic steelmaking furnace, refining slags, deoxidation and degassing, ladle metallurgy, alloying, and continuous casting of steel. Prerequisite: DCGN209 or MTGN351. 3 hours lecture; 3 semester hours. (Fall of even years only.).

**MTGN531. THERMODYNAMICS OF METALLURGICAL AND MATERIALS PROCESSING. 3.0 Semester Hrs.**
(I) Application of thermodynamics to the processing of metals and materials, with emphasis on the use of thermodynamics in the development and optimization of processing systems. Focus areas will include entropy and enthalpy, reaction equilibrium, solution thermodynamics, methods for analysis and correlation of thermodynamics data, thermodynamic analysis of phase diagrams, thermodynamics of surfaces, thermodynamics of defect structures, and irreversible thermodynamics. Attention will be given to experimental methods for the measurement of thermodynamic quantities. Prerequisite: MTGN351. 3 hours lecture; 3 semester hours.

**MTGN532. PARTICULATE MATERIAL PROCESSING I - COMMINUTION AND PHYSICAL SEPARATIONS. 3.0 Semester Hrs.**
An introduction to the fundamental principles and design criteria for the selection and use of standard mineral processing unit operations in comminution and physical separation. Topics covered include: crushing (jaw, cone, gyratory), grinding (ball, pebble, rod, SAG, HPGR), screening, thickening, sedimentation, filtration and hydrocyclones. Two standard mineral processing plant-design simulation software (MinOCad and JK SimMet) are used in the course. Prerequisites: Graduate or Senior in good- standing. 3 hours lecture, 3 semester hours.

**MTGN533. PARTICULATE MATERIAL PROCESSING II - APPLIED SEPARATIONS. 3.0 Semester Hrs.**
An introduction to the fundamental principles and design criteria for the selection and use of standard mineral processing unit operations in applied separations. Topics covered include: photometric ore sorting, magnetic separation, dense media separation, gravity separation, electrostatic separation and flotation (surface chemistry, reagents selection, laboratory testing procedures, design and simulation). Two standard mineral processing plant-design simulation software (MinOCad and JK SimMet) are used in the course. Graduate or Senior in good-standing. 3 hours lecture, 3 semester hours.

**MTGN535. PYROMETALLURGICAL PROCESSES. 0-3 Semester Hr.**
(II) Detailed study of a selected few processes, illustrating the application of the principles of physical chemistry (both thermodynamics and kinetics) and chemical engineering (heat and mass transfer, fluid flow, plant design, fuel technology, etc.) to process development. Prerequisite: none. 3 hours lecture; 3 semester hours.

**MTGN536. OPTIMIZATION AND CONTROL OF METALLURGICAL SYSTEMS. 3.0 Semester Hrs.**
Application of modern optimization and control theory to the analysis of specific systems in extractive metallurgy and mineral processing. Mathematical modeling, linear control analysis, dynamic response, and indirect optimum seeking techniques applied to the process analysis of grinding, screening, filtration, leaching, precipitation of metals from solution, and blast furnace reduction of metals. Prerequisite: none. 3 hours lecture; 3 semester hours.

**MTGN537. ELECTROMETALLURGY. 3.0 Semester Hrs.**
(II) Electrochemical nature of metallurgical processes. Kinetics of electrode reactions. Electrochemical oxidation and reduction. Complex electrode reactions. Mixed potential systems. Cell design and optimization of electrometallurgical processes. Batteries and fuel cells. Some aspects of corrosion. Prerequisite: none. 3 hours lecture; 3 semester hours. (Spring of even years only.).

**MTGN538. HYDROMETALLURGY. 3.0 Semester Hrs.**
(II) Kinetics of liquid-solid reactions. Theory of uniformly accessible surfaces. Hydrometallurgy of sulfide and oxides. Cementation and hydrogen reduction. Ion exchange and solvent extraction. Physicochemical phenomena at high pressures. Microbiological metallurgy. Prerequisite: none. 3 hours lecture; 3 semester hours. (Spring of odd years only.).

**MTGN539. PRINCIPLES OF MATERIALS PROCESSING REACTOR DESIGN. 3.0 Semester Hrs.**
(II) Review of reactor types and idealized design equations for isothermal conditions. Residence time functions for nonreacting and reacting species and its relevance to process control. Selection of reactor type for a given application. Reversible and irreversible reactions in CSTR's under nonisothermal conditions. Heat and mass transfer considerations and kinetics of gas-solid reactions applied to fluo-solids type reactors. Reactions in packed beds. Scale up and design of experiments. Brief introduction into drying, crystallization, and bacterial processes. Examples will be taken from current metallurgical practice. Prerequisite: none. 3 hours lecture; 3 semester hours. (Spring of odd years only.).

**MTGN540. MAGNETIC MATERIALS AND MODERN TECHNOLOGIES. 3.0 Semester Hrs.**
Every material is magnetic – although only some of them have useful magnetism. This course is designed to provide a practical view of magnetism in materials science, starting with the fundamentals of magnetism and classification of magnetic materials. We will discuss the fundamentals of magnetism, atomistic origins of magnetism and materials, and applications of magnetism in modern technologies. Throughout the course, we will interrogate how magnetism affects a materials bonding, structure, and functionality.
**Course Learning Outcomes**

- Explain the fundamentals of magnetism as they relate to materials using classical physics and quantum mechanics.
- Classify materials according to their field- and temperature-dependent magnetic behavior.
- Describe the underlying physics of uncorrelated and correlated systems using empirical theories.
- Predict the magnetic response of simple systems.
- Describe how magnetism can be exploited for technological applications.
- Plot and analyze magnetic data in Python.

**MTGN545. FATIGUE AND FRACTURE. 3.0 Semester Hrs.**
(I) Basic fracture mechanics as applied to engineering materials, S-N curves, the Goodman diagram, stress concentrations, residual stress effects, effect of material properties on mechanisms of crack propagation. Prerequisite: none. 3 hours lecture; 3 semester hours. (Fall of odd years only.).

**MTGN545L. MECHANICAL PROPERTIES OF MATERIALS LABORATORY. 3.0 Semester Hrs.**
Laboratory sessions devoted to advanced mechanical-testing techniques to illustrate the application of the fundamentals presented in the lectures of MTGN445. 3 hours lab; 1 semester hour. Co-requisite: MTGN598H.
**Course Learning Outcomes**

- Same as existing MTGN445L

**MTGN548. TRANSFORMATIONS IN METALS. 3.0 Semester Hrs.**
(I) Surface and interfacial phenomena, order of transformation, grain growth, recovery, recrystallization, solidification, phase transformation in solids, precipitation hardening, spinoidal decomposition, martensitic transformation, gas metal reactions. Prerequisite: none. 3 hours lecture; 3 semester hours. (Fall of odd years only.).

**MTGN549. CURRENT DEVELOPMENTS IN FERROUS ALLOYS. 3.0 Semester Hrs.**
(I) Development and review of solid state transformations and strengthening mechanisms in ferrous alloys. Application of these principles to the development of new alloys and processes such as high strength low alloy steels, high temperature alloys, maraging steels, and case hardening processes. Prerequisite: MTGN348. 3 hours lecture; 3 semester hours.

**MTGN551. ADVANCED CORROSION ENGINEERING. 3.0 Semester Hrs.**
(I) Advanced topics in corrosion engineering. Case studies and industrial application. Special forms of corrosion. Advanced measurement techniques. Prerequisite: MTGN451. 3 hours lecture; 3 semester hours. (Fall of even years only.).

**MTGN553. STRENGTHENING MECHANISMS. 3.0 Semester Hrs.**
(II) Strain hardening in polycrystalline materials, dislocation inter actions, effect of grain boundaries on strength, solid solution hardening, martensitic transformations, precipitation hardening, point defects. Prerequisite: MTGN543 or concurrent enrollment. 3 hours lecture;3 semester hours. (Spring of even years only.).

**MTGN555. SOLID STATE THERMODYNAMICS. 3.0 Semester Hrs.**
(I) Thermodynamics applied to solid state reactions, binary and ternary phase diagrams, point, line and planar defects, interfaces, and electrochemical concepts. Prerequisite: none. 3 hours lecture; 3 semester hours.

**MTGN556. TRANSPORT IN SOLIDS. 3.0 Semester Hrs.**
(I) Thermal and electrical conductivity. Solid state diffusion in metals and metal systems. Kinetics of metallurgical reactions in the solid state. Prerequisite: none. 3 hours lecture; 3 semester hours. (Spring of even years only.).

**MTGN556L. ELECTRON MICROSCOPY LABORATORY. 3.0 Semester Hrs.**
Laboratory exercises to illustrate specimen preparation techniques, microscope operation, and the interpretation of images produced from a variety of specimens, and to supplement the lectures in MTGN456. 3 hours lab; 1 semester hour. Co-requisite: MTGN598I.
**Course Learning Outcomes**

- Same as existing MTGN456L outcomes.

**MTGN557. SOLIDIFICATION. 3.0 Semester Hrs.**
(I) Heat flow and fluid flow in solidification, thermodynamics of solidification, nucleation and interface kinetics, grain refining, crystal and grain growth, constitutional supercooling, eutectic growth, solidification of castings and ingots, segregation, and porosity. Prerequisite: none. 3 hours lecture; 3 semester hours. (Fall of odd years only.).

**MTGN560. ANALYSIS OF METALLURGICAL FAILURES. 3.0 Semester Hrs.**
(II) Applications of the principles of physical and mechanical metallurgy to the analysis of metallurgical failures. Nondestructive testing. Fractography. Case study analysis. Prerequisite: none. 3 hours lecture; 3 semester hours. (Spring of odd years only.).

**MTGN564. ADVANCED FORGING AND FORMING. 3.0 Semester Hrs.**
(II) Overview of plasticity. Examination and Analysis of working operations of forging, extrusion, rolling, wire drawing and sheet metal forming. Metallurgical structure evolution during working. Laboratory experiments involving metal forming processes. Prerequisites: MTGN445/ MLGN505, 2 hours lecture; 3 hours lab, 3 semester hours.

**MTGN565. MECHANICAL PROPERTIES OF CERAMICS AND COMPOSITES. 3.0 Semester Hrs.**
(I) Mechanical properties of ceramics and ceramic-based composites; brittle fracture of solids; toughening mechanisms in composites; fatigue, high temperature mechanical behavior, including fracture, creep deformation. Prerequisites: MTGN445 or MLGN505. 3 hours lecture; 3 semester hours. (Fall of even years only.).

**MTGN569. FUEL CELL SCIENCE AND TECHNOLOGY. 3.0 Semester Hrs.**
Equivalent with CBEN569,MEGN569,MLGN569,
(I) Investigate fundamentals of fuel-cell operation and electrochemistry from a chemical-thermodynamics and materials- science perspective. Review types of fuel cells, fuel-processing requirements and approaches, and fuel-cell system integration. Examine current topics in fuel-cell science and technology. Fabricate and test operational fuel cells in the Colorado Fuel Cell Center. 3 credit hours.

**MTGN570. BIOCOMPATIBILITY OF MATERIALS. 3.0 Semester Hrs.**
Introduction to the diversity of biomaterials and applications through examination of the physiologic environment in conjunction with compositional and structural requirements of tissues and organs. Appropriate domains and applications of metals, ceramics and polymers, including implants, sensors, drug delivery, laboratory automation, and tissue engineering are presented. Prerequisites: BIOL110 or equivalent. 3 hours lecture; 3 semester hours.

**MTGN572. BIOMATERIALS. 3.0 Semester Hrs.**
Equivalent with MLGN572,
A broad overview on materials science and engineering principles for biomedical applications with three main topics: 1) The fundamental properties of biomaterials; 2) The fundamental concepts in biology; 3) The interactions between biological systems with exogenous materials. Examples including surface energy and surface modification; protein adsorption; cell adhesion, spreading and migration; biomaterials implantation and acute inflammation; blood-materials interactions and thrombosis; biofilm and biomaterials-related pathological reactions. Basic principles of bio-mimetic materials synthesis and assembly will also be introduced. 3 hours lecture; 3 semester hours.

**MTGN573. COMPUTATIONAL MATERIALS. 3.0 Semester Hrs.**
(II) Computational Materials is a course designed as an introduction to computational approaches and codes used in modern materials science and engineering, and to provide the hands?on experience in using massively parallel supercomputers and popular materials software packages. The main goal is to provide exposure to students to the growing and highly interdisciplinary field of computational materials science and engineering, through a combination of lectures, hands-on exercises and a series of specifically designed projects. The course is

organized to cover different length scales including: atomistic (electronic structure) calculations, molecular dynamics, and phase equilibria modeling. The emerging trends in data driven materials discovery and design are also covered. Particular emphasis is placed on the validation of computational results and recent trends in integrating theory, computations and experiment. Graduate students are expected to successfully complete 4 projects while the undergraduate students are required to finish 3 out of 4 projects. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Module 1: 1. Introduction to computational materials science and engineering
- Module 2: Electronic structure calculations
- Module 3: Molecular dynamics calculations
- Module 4: Materials thermodynamics and phase equilibria modeling

**MTGN575. METALLURGY OF WELDING. 3.0 Semester Hrs.**
This class includes both lecture and lab sessions for you to build an in-depth understanding of industrial welding and joining processes, especially the metallurgical aspects, and gain hands-on experience in commonly used welding technologies through project-based training.
**Course Learning Outcomes**

- It will provide students an opportunity to gain an overall view of industrial operations, build a sound background in the key manufacturing processes, become aware of the frontiers of welding research, and be prepared to extend the scientific frontiers in the field of welding and transfer the knowledge to additive manufacturing.

**MTGN580. ADVANCED WELDING METALLURGY. 3.0 Semester Hrs.**
(II) Weldability of high strength steels, high alloys, and light metals; Welding defects; Phase transformations in weldments; Thermal experience in weldments; Pre- and Post-weld heat treatment; Heat affected zone formation, microstructure, and properties; Consumables development. Prerequisite: none. 3 hours lecture; 3 semester hours. (Spring of odd years only.).

**MTGN593. NUCLEAR MATERIALS SCIENCE AND ENGINEERING. 3.0 Semester Hrs.**
(I) Introduction to the physical metallurgy of nuclear materials, including the nuclear, physical, thermal, and mechanical properties for nuclear materials, the physical and mechanical processing of nuclear alloys, the effect of nuclear and thermal environments on structural reactor materials and the selection of nuclear and reactor structural materials are described. Selected topics include ceramic science of ceramic nuclear material, ceramic processing of ceramic fuel, nuclear reaction with structural materials, radiation interactions with materials, the aging of nuclear materials, cladding, corrosion and the manufacturing of fuels elements. Relevant issues in the modern fuel cycle will also be introduced including nuclear safety, reactor decommissioning, and environmental impacts. Prerequisites: Graduate or Senior in good-standing. 3 hours lecture, 3 semester hours. (Fall of even years only.).

**MTGN598. SPECIAL TOPICS IN METALLURGICAL AND MATERIALS ENGINEERING. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**MTGN598. SPECIAL TOPICS. 0-6 Semester Hr.**

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**MTGN598. MECHANICAL PROPERTIES OF MATERIALS. 3.0 Semester Hrs.**
Mechanical properties and relationships. Plastic deformation of crystalline materials. Relationships of microstructures to mechanical strength. Fracture, creep, and fatigue. 3 hours lecture, 3 semester hours. Prerequisite: MTGN348 and CEEN241 and CEEN311. Co-requisite: MTGN598HL.
**Course Learning Outcomes**

- No changes to current class outcomes

**MTGN598. ELECTRON MICROSCOPY. 2.0 Semester Hrs.**
Introduction to electron optics and the design and application of transmission and scanning electron microscopes. Interpretation of images produced by various contrast mechanisms. Electron diffraction analysis and the indexing of electron diffraction patterns. 2 hours lecture; 2 semester hours. Prerequisite: MTGN211. Co-requisite: MTGN556L.
**Course Learning Outcomes**

- No changes to current class outcomes

**MTGN598LA. SPECIAL TOPICS LAB. 1-3 Semester Hr.**

**MTGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**MTGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

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**MTGN605. ADVANCED TRANSMISSION ELECTRON MICROSCOPY. 2.0 Semester Hrs.**
Introduction to transmission electron microscopy techniques and their application to materials characterization. Topics include electron optics, electron-specimen interactions, imaging, diffraction, contrast mechanisms, defect analyses, compositional measurements using energy dispersive x-ray spectroscopy and energy loss spectroscopy, scanning transmission electron microscopy, high angle annular dark field imaging, energy filtered TEM and high resolution phase contrast

imaging. 2 hours lecture, 2 semester hours. Prerequisites: MLGN593. Co-requisites: MTNG605L.

**MTGN605L. ADVANCED TRANSMISSION ELECTRON MICROSCOPY LABORATORY. 1.0 Semester Hr.**
Specimen preparation techniques and their application to materials characterization. Topics include electron optics, electron-specimen interactions, imaging, diffraction, contrast mechanisms, defect analyses, compositional measurements using energy dispersive x-ray spectroscopy and energy loss spectroscopy, scanning transmission electron microscopy, high angle annular dark field imaging, energy filtered TEM and high resolution phase contrast imaging. 3 hours lab, 1 semester hour. Co-requisites: MTGN605.

**MTGN631. TRANSPORT PHENOMENA IN METALLURGICAL AND MATERIALS SYSTEMS. 3.0 Semester Hrs.**
Physical principles of mass, momentum, and energy transport. Application to the analysis of extraction metallurgy and other physicochemical processes. Prerequisite: MATH225 and MTGN461 or equivalent. 3 hours lecture; 3 semester hours.

**MTGN656. ADVANCED ELECTRON MICROSCOPY. 2.0 Semester Hrs.**
Advanced introduction to electron optics and the design and application of transmission and scanning electron microscopes. Interpretation of images produced by various contrast mechanisms. Electron diffraction analysis and the indexing of electron diffraction patterns. Co-requisite: MTGN656L.
**Course Learning Outcomes**

**MTGN656L. ADVANCED ELECTRON MICROSCOPY LABORATORY. 1.0 Semester Hr.**
Laboratory exercises to illustrate specimen preparation techniques, microscope operation, and the interpretation of images produced from a variety of specimens, and to supplement the lectures in MTGN456. Co-requisite: MTGN656.
**Course Learning Outcomes**

**MTGN698. SPECIAL TOPICS IN METALLURGICAL AND MATERIALS ENGINEERING. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**MTGN699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**MTGN700. GRADUATE RESEARCH CREDIT: MASTER OF ENGINEERING. 1-6 Semester Hr.**
(I, II, S) Research credit hours required for completion of the degree Master of Engineering. Research under the direct supervision of a faculty advisor. Credit is not transferable to any 400, 500, or 600 level courses. However, MTGN 705 credit hours may be transferred, in accordance with the requirements for this (M.E.) degree, by a Master of Science graduate-student who previously accumulated these credit-hours and subsequently opted to change their degree program to a Master of Engineering. Repeatable for credit. Variable: 1 to 6 semester hours.

**MTGN707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.**
(I, II, S) Research credit hours required for completion of a Masters-level thesis or Doctoral dissertation. Research must be carried out under the direct supervision of the student's faculty advisor. Variable class and semester hours. Repeatable for credit.

## Professors

Geoff Brennecka, Director of the Colorado Center for Advanced Ceramics

Kip O. Findley, Director of the Advanced Steel Processing and Products Research Center (ASPPRC), John Henry Moore Chair

Brian P. Gorman

Michael J. Kaufman, Co-Director of the Center for Advanced Non-Ferrous Structural Alloys (CANFSA)

Suveen N. Mathaudhu, Director of the Center for Advanced Non-Ferrous Structural Alloys (CANFSA)

Emmanuel De Moor

Ryan O'Hayre, University Distinguished Professor

Ivar E. Reimanis, Department Head, George S. Ansell Distinguished Chair

John G. Speer, American Bureau of Shipping Endowed Chair in Metallurgical and Materials Engineering

## Associate Professors

Vladan Stevanovic

Zhenzhen Yu, Director of the Center for Welding, Joining and Coatings Research (CWJCR)

## Assistant Professors

Lawrence Cho

Xiaolei Guo

Megan Holtz

Jihye Kim

Jonah Klemm-Toole

Eve Mozur

Anna Staerz

## Teaching Professors

Gerald Bourne, Associate Department Head, Charles F. Fogarty Limited Professorship

Kimberly Scott

## Research Faculty and Joint Appointments

Corby G. Anderson

Amy Clarke

Kester Clarke

Arun Devaraj

David Diercks

David Ginley

Prashun Gorai

Steve Harvey

Jeffrey King

Jaeheon Lee

Terry Lowe

Stephen Midson

Corinne Packard

Michael Sanders

Erik Spiller

Steve Spurgeon

Judith Gomez Vidal

Andriy Zakutayev

## Affiliate Faculty

Adam Creuziger

C. Matthew Enloe

Ron Goldfarb

Andrew Kustas

Nathan Orloff

Terry Totemeier

## Professors Emeriti

Glen R. Edwards, University Professor Emeritus

John P. Hager, University Professor Emeritus

George Krauss, University Professor Emeritus

Stephen Liu, University Professor Emeritus, Inaugural American Bureau of Shipping Chair Professor

Gerard P. Martins, Professor Emeritus

David K. Matlock, University Professor Emeritus

Brajendra Mishra, University Professor Emeritus

John J. Moore, Professor Emeritus

David L. Olson, University Professor Emeritus

Dennis W. Readey, University Professor Emeritus

Angus Rockett, University Professor Emeritus

Patrick R. Taylor, Professor Emeritus

Chester J. Van Tyne, Professor Emeritus

## Associate Professors Emeriti

Gerald L. DePoorter

Robert H. Frost

Steven W. Thompson

# Mining Engineering

## Degrees Offered

- Graduate Certificate in Tailings Engineering
- Professional Masters Program in Mining Industry Management
- Master of Science in Mining Engineering (thesis or non-thesis)
- Master of Science in Earth Resources Science and Engineering (thesis or non-thesis)
- Doctor of Philosophy in Mining Engineering
- Doctor of Philosophy in Earth Resources Science and Engineering

## Program Description

The program has two distinctive, but inherently interwoven specialties.

The **Mining Engineering** area or specialty is predominantly for mining engineers, and it is directed toward the traditional mining engineering fields. Graduate work is normally centered around subject areas such as mine planning and development, computer-aided mine design, rock mechanics, operations research applied to the mineral industry, environment and sustainability considerations, mine mechanization, mine evaluation, finance and management, and similar mining engineering topics.

The **Earth Resources Science and Engineering** specialty is for those who wish to specialize in interdisciplinary fields that include understanding emerging technical and social issues in Earth Resources Development Engineering. This specialty is open to students with mining or non-mining engineering undergraduate degrees who are interested in scholarship and research on topics including, but not limited to, mining and sustainability, mine closure and reclamation engineering, corporate social responsibility, artisanal and small-scale mining, underground construction and tunneling engineering, mining and the environment, modeling and design in earth systems and processes, geothermal, explosive engineering, mine and construction management, mining-related data science, earth observation for mine environmental monitoring and design and application of sensor networks, Internet of Things (IoT), robotics, and Artificial Intelligence (AI) for autonomous mine systems. Because of the interdisciplinary nature of this degree program, students will be required to take three core classes in the Mining Engineering Department and then choose courses related to their area of interest offered by mining, as well as other departments across campus.

Graduate work is normally centered on subject areas.

## Mining Engineering Program Description

Regarding academics and research the Mining Engineering Department focuses on fundamental areas including:

- Geomechanics, rock mechanics and stability of underground and surface excavations
- Computerized mine design and related applications (including geostatistical modeling)
- Advanced integrated mining systems incorporating mine mechanization and mechanical mining systems
- Underground excavation, tunneling, and construction
- Construction and project management
- Site characterization and geotechnical investigations, modeling and design in geoengineering
- Rock fragmentation
- Mineral processing, comminution, and separation technology
- Extractive and chemical metallurgy for metals processing and recovery
- Tailings and mine waste
- Bulk material handling
- Mine ventilation
- Mine safety and health
- Corporate social responsibility and sustainability
- Artisanal and small-scale Mining

## Program Requirements

The Master of Science degree in Mining Engineering requires 30 credits of coursework and has two options available, thesis and non-thesis.

For the PhD degree, students holding an MS degree in an appropriate field may transfer, with the approval of the graduate advisor and the doctoral committee, a maximum of 30 credits of graduate coursework toward the credits to be completed for the PhD. The doctoral dissertation must be successfully defended before the approved doctoral committee.

## Mining Engineering (MNEG) Degree Requirements

### Master of Science – Thesis (MS-T)

Students in the Mining Engineering MS-T degree program must take a minimum of 12 course credits of the 21-credit requirement from within the Mining Engineering Department. These must include the core requirement courses listed below, unless waived by the master's thesis committee.

### Master of Science - Non-thesis (MS-NT)

Students in the Mining Engineering MS-NT program must take a minimum of 21 credits of coursework from within Mining Engineering Department. These must include the core requirement courses listed below unless waived.

## Mines' Combined Undergraduate/Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

## Doctor of Philosophy

Maximum of 48 semester credits of coursework is required. A maximum of 30 units can be transferred from an MS degree program. The student's graduate committee must approve the transfer of these units. A minimum of 18 credit courses must be taken in the Mining Engineering Department.

| | |
|---|---|
| Coursework credits (minimum) | 48.0 |
| Research credits (minimum) | 24.0 |
| **Credits beyond the BS degree (required)** | **72.0** |

## Other PhD Requirements

- A minimum of 18 hours of coursework must be completed at Colorado School of Mines. A minimum of 9 credits beyond the master's degree must be completed in the Mining Engineering Department. Exceptions may be approved by the PhD dissertation committee.
- Those with an MS in an appropriate field may transfer a maximum of 30 credits of coursework towards the coursework requirement, subject to the approval by the advisor and doctoral committee.
- The doctoral dissertation thesis must be successfully defended before the doctoral committee.
- Assessment Exam, usually taken at the end of the first year in the PhD program.
- Minimum GPA requirement: 3.0/4.0.
- Thesis proposal ppproval.
- Comprehensive Exams, oral mandatory, and written may be waived at the discretion of the doctoral committee.

## Required Core Courses for either the MS or PhD degree:

Two of the following three graduate courses are required to be completed to receive a Mining Engineering graduate degree at Mines:

| | | |
|---|---|---|
| MNGN508 | ADVANCED ROCK MECHANICS | 3.0 |
| MNGN512 | SURFACE MINE DESIGN | 3.0 |
| MNGN516 | UNDERGROUND MINE DESIGN | 3.0 |
| MNGN625 | GRADUATE MINING SEMINAR | 1.0 |

## Prerequisites

Students entering the Mining Engineering graduate program for either the master's or doctoral degree are expected to have completed an undergraduate ABET-accredited BS degree in Mining Engineering. Deficiencies, if any, will be determined by the Department of Mining Engineering on the basis of a student's academic record and experience. For specific information on prerequisites, students are encouraged to refer to the Mining Engineering Department's Graduate Handbook, available from the Department of Mining Engineering or on the webpage at https://mining.mines.edu/graduate-program/.

## Earth Resources Science and Engineering Program Description

The Earth Resources Science and Engineering specialty is for those who wish to specialize in interdisciplinary fields that include understanding emerging technical and social issues in Earth Resources Science and Engineering . This specialty is open to students with undergraduate degrees in mining, science backgrounds and engineering disciplines who are interested in scholarship and research on topics including, but not limited to, mining and sustainability, mine closure and reclamation engineering, corporate social responsibility, artisanal and small-scale mining, underground construction and tunneling engineering, mining and the environment, tailings and mine waste, modeling and design in earth systems and processes, geothermal, explosive engineering, mine and construction management, mining related data science, earth observation for mine environmental monitoring and design and application of sensor networks, Internet of Things (IoT), robotics, and Artificial Intelligence (AI) for autonomous mine systems. Because of the interdisciplinary nature of this degree program, students will be required to take three core classes in the Mining Engineering Department and then choose courses related to their area of interest offered by mining, as well as other departments across campus.

The Master of Science in Earth Resources Science and Engineering has two MS degree options (thesis and non-thesis). For the PhD degree, students holding an MS degree in a relevant field may transfer, with the approval of the doctoral committee, a maximum of 30 credits of graduate coursework toward the required credits for the PhD degree. The doctoral dissertation must be successfully defended before the approved doctoral committee.

## Earth Resource Science and Engineering (ERSE) Degree Requirements

### Master of Science – Thesis (MS-T)

Students in the ERSE MS-T program must take a minimum of 15 credits from within the Mining Engineering Department. These must include the required core courses listed below unless waived by the master's thesis committee.

| | |
|---|---|
| Coursework credits (minimum) | 21.0 |
| Research credits (maximum) | 9.0 |
| **Total credits (minimum)** | **30.0** |

### Master of Science - Non-Thesis (MS-NT)

Students in the ERSE MS-NT program must take a minimum of 15 credits of coursework from within Mining Engineering Department. These must include the required core courses listed below unless waived.

| | |
|---|---|
| **Total course work credits (minimum)** | **30.0** |

## Mines' Combined Undergraduate/Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

## Doctor of Philosophy

Maximum of 48 semester credits of coursework, where a maximum of 30 units can be transferred from a MS degree program. The student's graduate committee must approve the transfer of these units. A minimum of 9 credit courses must be taken in the Mining Engineering Department. These must include the required core courses listed below unless waived.

| | |
|---|---|
| Coursework credits (minimum) | 48.0 |
| Research credits (minimum) | 24.0 |
| **Credits beyond the BS degree (required)** | **72.0** |

## Other PhD Requirements

- A minimum of 18 hours of coursework must be completed at Colorado School of Mines. A minimum of 9 credits beyond the master's degree must be completed in the Mining Engineering Department. Exceptions may be approved by the PhD dissertation committee.
- Those with an MS in an appropriate field may transfer a maximum of 30 credits of coursework toward the coursework requirement, subject to the approval by the advisor and doctoral committee.
- The doctoral dissertation thesis must be successfully defended before the doctoral committee.
- Assessment Exam, usually taken at the end of the first year in the PhD program.
- Minimum GPA requirement: 3.0/4.0.
- Thesis proposal approval.
- Comprehensive Exams, oral mandatory, and written may be waived at the discretion of the doctoral committee.

## Required Core Courses for either the MS or PhD degree:

***The following courses are required:***

| | | |
|---|---|---|
| MNGN510 | FUNDAMENTALS OF MINING AND MINERAL RESOURCE DEVELOPMENT | 3.0 |
| MNGN625 | GRADUATE MINING SEMINAR | 1.0 |

***In addition, two of the following four courses are required:***

| | | |
|---|---|---|
| MNGN567 | SUSTAINABLE DEVELOPMENT AND EARTH RESOURCES | 3.0 |
| MNGN556 | MINE WATER AND ENVIRONMENT | 3.0 |
| MNGN502 | GEOSPATIAL BIG DATA ANALYTICS | 3.0 |
| MNGN528 | MINING GEOLOGY | 3.0 |
| MNGN541 | ELECTROMETALLURGY | 3.0 |
| MNGN542 | HYDROMETALLURGY | 3.0 |
| MNGN527 | SOLID WASTE MINIMIZATION AND RECYCLING | 3.0 |

## Prerequisites

Students entering the ERSE graduate program for either the master's or doctoral degree are expected to have completed the equivalent of an undergraduate ABET-accredited BS degree in some discipline of engineering. Deficiencies, if any, will be determined by the Department of Mining Engineering on the basis of a student's academic record and experience. For specific information on prerequisites, students are

encouraged to refer to the Mining Engineering Department's Graduate Handbook, available from the Department of Mining Engineering or on the webpage at https://mining.mines.edu/graduate-program/.

## Professional Master's in Mining Industry Management (MP-MIM) Program Description and Degree Requirements

The PM in Mining Industry Management is being offered fully online. It is not offered on campus. It is a unique and competitive degree offering that stands alone among graduate mining engineering programs (as well as MBA programs) at domestic and international institutions. This new degree does not replace existing graduate programs that focus on technical development and research, but provides a unique choice for students with managerial and business aspirations to obtain an advanced education in the mining and mineral industries. As a fully online graduate program, the PM is not offered on campus. It is open to anyone who has a bachelor's degree plus at least five years of experience in the mining sector. There is no premium cost for students who reside outside Colorado or outside the United States, and this program does not require students to ever travel to the Mines campus. Students accepted into the program join a cohort, which has the opportunity to take all the program courses in sequence over a two and a half-year period. See https://mining.mines.edu/professionalmasters/ for more information. Graduates from the program will be offered the opportunity to attend commencement ceremony where their degree will be conferred upon them. Online delivery will give the program a competitive edge by offering the flexible schedule necessary to attract professionals in full-time employment or others that cannot leave their place of residence.

The PM curriculum content was developed by Mining Engineering and adjunct faculty, based on discussions with the Mining Engineering department's industry advisory committee, education professionals, and members of the mining industry.

The curriculum includes 15 courses (3 of which comprise the independent capstone project - MNGN572A-C) encompassing 33 credits. Course content is guided by the vision and values of Mines and the Mining Engineering Department.

The following PM courses are designated with priority registration for students enrolled in the online Professional Master's in Mining Industry Management program. If a student would like to take a particular PM course and is not enrolled in the PM program, they should send an email to PM-MIM@mines.edu requesting approval to take the course. Acceptance into the courses will be based on capacity and consent of instructor.

| | | |
|---|---|---|
| MNGN553 | MINE DESIGN AND OPERATION PLANNING | 3.0 |
| MNGN548 | INFORMATION TECHNOLOGIES FOR MINING SYSTEMS | 3.0 |
| MNGN547 | GEOLOGY AND MINING | 3.0 |
| MNGN558 | MINERAL PROCESSING | 3.0 |
| MNGN546 | MINE HEALTH AND SAFETY | 2.0 |
| MNGN562 | MINING ENVIRONMENTAL AND SOCIAL RESPONSIBILITY | 2.0 |
| MNGN563 | WATER WASTE AND MINE CLOSURE | 3.0 |
| MNGN551 | MINE ACCOUNTING | 2.0 |
| MNGN554 | MINE FINANCE | 2.0 |
| MNGN557 | MINERAL ECONOMICS AND POLICY | 2.0 |
| MNGN561 | PROJECT MANAGEMENT | 3.0 |
| MNGN555 | MINE INVESTMENT EVALUATION | 3.0 |
| MNGN572A | MINING INDUSTRY MANAGEMENT CAPSTONE DESIGN | 0.5 |
| MNGN572B | MINING INDUSTRY MANAGEMENT CAPSTONE DEVELOPMENT | 0.5 |
| MNGN572C | MINING INDUSTRY MANAGEMENT CAPSTONE DELIVERY - FINAL SECTION | 1.0 |
| **Total Semester Hrs** | | **33.0** |

The program was developed to meet the world's evolving challenges related to the Earth, energy, and the environment, and to address the needs of the world's growing population to recover and conserve the Earth's resources. The curriculum confirms Colorado School of Mines as an internationally recognized leader in engineering education, by providing a unique educational experience that collaborates with industry to prepare graduates for leadership in the mining and mineral industries.

Based on the faculty's assessment of the changes in emerging technical, social, and economic factors present in developing a mineral resource, the Colorado School of Mines curriculum should remain the product of choice for domestic and international professional education for the mining industry.

## Graduate Certificate in Tailings Engineering

Tailings Engineering specialty is for those who wish to specialize in interdisciplinary fields that include understanding emerging technical and social issues in this discipline. This specialty is open to students with mining or non-mining engineering undergraduate degrees who are interested in scholarship and research on topics including, but not limited to, geology, geotechnical engineering, water, soil mechanics, tailing valorization, mineral processing and extractive metallurgy, environmental engineering, and social governance.

Because of the interdisciplinary nature of this degree program, students will be required to take two required courses in the Department of Mining Engineering and then choose two courses related to their area of interest offered by mining, as well as other departments across campus. The certificate program can be completed by taking 12 credits of graduate coursework.

**REQUIRED COURSES:**

| | | |
|---|---|---|
| MNGN581 | FUNDAMENTALS OF TAILINGS ENGINEERING I | 3.0 |
| MNGN582 | FUNDAMENTALS OF TAILINGS ENGINEERING II | 3.0 |

## Electives

Please select two courses from the following list of Elective Clusters:

| | | |
|---|---|---|
| **Mining/Mineral Processing & Extractive Metallurgy** | | |
| MNGN532 | PARTICULATE MATERIAL PROCESSING I - COMMINUTION AND PHYSICAL SEPARATIONS | 3.0 |
| MNGN541 | ELECTROMETALLURGY | 3.0 |
| MNGN542 | HYDROMETALLURGY | 3.0 |
| MNGN563 | WATER WASTE AND MINE CLOSURE | 3.0 |
| MNGN556 | MINE WATER AND ENVIRONMENT | 3.0 |
| **Civil & Environmental Engineering** | | |
| CEEN515 | HILLSLOPE HYDROLOGY AND STABILITY | 3.0 |
| CEEN519 | RISK ASSESSMENT IN GEOTECHNICAL ENGINEERING | 3.0 |

| | | |
|---|---|---|
| CEEN581 | WATERSHED SYSTEMS MODELING | 3.0 |
| CEEN573 | RECLAMATION OF DISTURBED LANDS | 3.0 |
| **Geochemistry** | | |
| CHGC503 | INTRODUCTION TO GEOCHEMISTRY | 3.0 |
| CHGC504 | METHODS IN GEOCHEMISTRY | 3.0 |
| CHGC508 | ANALYTICAL GEOCHEMISTRY | 3.0 |
| CHGC509 | INTRODUCTION TO AQUEOUS GEOCHEMISTRY | 3.0 |
| **Geophysics** | | |
| GPGN530 | APPLIED GEOPHYSICS | 3.0 |
| GPGN570 | APPLICATIONS OF SATELLITE REMOTE SENSING | 3.0 |
| **ESG** | | |
| MNGN503 | MINING TECHNOLOGY FOR SUSTAINABLE DEVELOPMENT | 3.0 |
| MNGN562 | MINING ENVIRONMENTAL AND SOCIAL RESPONSIBILITY | 2.0 |
| MNGN567 | SUSTAINABLE DEVELOPMENT AND EARTH RESOURCES | 3.0 |
| MNGN571 | ENERGY, NATURAL RESOURCES, AND SOCIETY | 3.0 |
| **Geological Engineering** | | |
| GEGN542 | ADVANCED DIGITAL TERRAIN ANALYSIS | 3.0 |
| GEGN573 | GEOLOGICAL ENGINEERING SITE INVESTIGATION | 3.0 |
| GEGN575 | APPLICATIONS OF GEOGRAPHIC INFORMATION SYSTEMS | 3.0 |
| GEGN580 | APPLIED REMOTE SENSING FOR GEOENGINEERING AND GEOSCIENCES | 3.0 |
| GEGN582 | INTEGRATED SURFACE WATER HYDROLOGY | 3.0 |

Course substitutions require the approval of the Tailings Engineering graduate certificate program director.

## Courses

**MNGN501. REGULATORY MINING LAWS AND CONTRACTS. 3.0 Semester Hrs.**
(I) Basic fundamentals of engineering law, regulations of federal and state laws pertaining to the mineral industry and environment control. Basic concepts of mining contracts. Offered in even numbered years. Prerequisite: Senior or graduate status. 3 hours lecture; 3 semester hours. Offered in even years.

**MNGN502. GEOSPATIAL BIG DATA ANALYTICS. 3.0 Semester Hrs.**
Spatial data models (vector and raster data) and structures (R tree and octree data structures), characteristics of geospatial big data (e.g. satellite images, Lidar point clouds, sensor measurements, environmental monitoring data, socio-economic data), geospatial big data sources (IoT, sensors, images, Lidar, crowd-sources), geospatial big data life cycle, visualizations for geospatial big data sets, isual design principles (Bertin`s visual variables, preattentive attributes, Gestalt principles and Tufte`s design principles), the first order and second order exploration methods for various geospatial data (spatially discrete point data, spatially continuous point data and area data), machine learning algorithms (k-means clustering, self-organizing maps, support vector machines), statistical learning methods (point pattern analyses, kriging, non-spatial, spatial regression and geographically weighted regression).
**Course Learning Outcomes**

- Recognize main features of spatial data models (vector and raster data) and structures (R tree and octree data structures), recall the characteristics of geospatial big data and evaluate and compare various data sets (e.g. satellite images, Lidar point clouds, sensor measurements, environmental monitoring data, socio-economic data) in terms of the 5V`s (Volume, Velocity, Veracity, Variety and Value) of big data.
- Distinguish types of geospatial big data and its sources (IoT, sensors, images, Lidar, crowd-sources, etc.) in geosciences
- Apply incremental steps of geospatial big data life cycle to a given business case (e.g., monitoring land use and land cover change, decision making processes in geosciences, monitoring human behavior, etc.)
- Design at least three data visualizations for geospatial big data sets considering visual design principles (Bertin`s visual variables, preattentive attributes, Gestalt principles and Tufte`s design principles).
- Implement the first order and second order exploration methods for various geospatial data (spatially discrete point data, spatially continuous point data and area data)
- Apply machine learning algorithms (k-means clustering, self-organizing maps, support vector machines) to geospatial data sets.
- Implement statistical learning methods (point pattern analyses, kriging, non-spatial, spatial regression and geographically weighted regression) to geospatial data sets and identify the structure of big data frameworks used in management of the geospatial big data in geosciences

**MNGN503. MINING TECHNOLOGY FOR SUSTAINABLE DEVELOPMENT. 3.0 Semester Hrs.**
(I, II) The primary focus of this course is to provide students an understanding of the fundamental principles of sustainability and how they influence the technical components of a mine's life cycle, beginning during project feasibility and extending through operations to closure and site reclamation. Course discussions will address a wide range of traditional engineering topics that have specific
relevance and impact to local and regional communities, such as mining methods and systems, mine plant design and layout, mine operations and supervision, resource utilization and cutoff grades, and labor. The course will emphasize the
importance of integrating social, political, and economic considerations into technical decision-making and problem solving. 3 hours lecture; 3 semester hours.

**MNGN504. UNDERGROUND CONSTRUCTION ENGINEERING IN HARD ROCK. 3.0 Semester Hrs.**
This course is developed to introduce students to the integrated science, engineering, design and management concepts of engineered underground construction. The course will cover advanced rock engineering in application to underground construction, geological interpretation and subsurface investigations, tunneling method and equipment options and system selection for projects with realistic constraints, underground excavation initial support and final lining design, and approaches to uncertainty evaluation and risk assessment for underground construction projects. Team design projects and presentations will be required. Prerequisites: CEEN312 or MTGN321. Corequisites: GEGN462 or GEGN561.
**Course Learning Outcomes**

- Know the typical application of the underground space, Be aware of subsurface constraints and controlling parameters, be able select

project alignments, and understand the pros and cons of different subsurface conditions.

- Develop the ability to design a preliminary geotech site investigation plan, including the boring, as well as field and lab testing, along with the estimated costs.
- Be able to select tunneling method based on results of geotech investigation, have the practical knowledge of various tunneling methods in rock and variety of equipment, and operational settings in the tunneling projects.
- Understand the ground stresses, ground/support reaction curves, and be able to select and develop a preliminary design for ground support in rock.
- Be able to select the shaft and raise development methods in rock for different subsurface conditions.
- Be able to select the right application for conventional tunneling methods, develop blast round design for tunnel.
- know the options, pros and cons, and approaches to Sequential Excavation Method (SEM or NATM).
- Ability to select the right tunnel boring machine (TBM) for the given project and be able to estimate the penetration and daily advance rate.
- Be able to make an assessment of the potential for ground squeezing and rock burst in deep tunnels.
- Be able to offer a preliminary estimate of construction cost for tunnel, and develop a risk registry for rock tunnels.

**MNGN505. ROCK MECHANICS IN MINING. 3.0 Semester Hrs.**
(I) The course deals with the rock mechanics aspect of design of mine layouts developed in both underground and surface. Underground mining sections include design of coal and hard rock pillars, mine layout design for tabular and massive ore bodies, assessment of caving characteristics or ore bodies,
performance and application of backfill, and phenomenon of rock burst and its alleviation. Surface mining portion covers rock mass characterization, failure modes of slopes excavated in rock masses, probabilistic and deterministic approaches to design of slopes, and remedial measures for slope stability
problems. Prerequisite: MN321 or equivalent. 3 hours lecture; 3 semester hours.

**MNGN506. DESIGN AND SUPPORT OF UNDERGROUND EXCAVATIONS. 3.0 Semester Hrs.**
Design of underground excavations and support. Analysis of stress and rock mass deformations around excavations using analytical and numerical methods. Collections, preparation, and evaluation of insitu and laboratory data for excavation design. Use of rock mass rating systems for site characterization and excavation design. Study of support types and selection of support for underground excavations. Use of numerical models for design of shafts, tunnels and large chambers. Prerequisite: none. 3 hours lecture; 3 semester hours. Offered in odd years.

**MNGN507. ADVANCED DRILLING AND BLASTING. 3.0 Semester Hrs.**
(I) An advanced study of the theories of rock penetration including percussion, rotary, and rotary percussion drilling. Rock fragmentation including explosives and the theories of blasting rock. Application of theory to drilling and blasting practice at mines, pits, and quarries. Prerequisite: MNGN407. 3 hours lecture; 3 semester hours. Offered in odd years.

**MNGN508. ADVANCED ROCK MECHANICS. 3.0 Semester Hrs.**
Equivalent with MNGN418,
(I, II, S) Analytical and numerical modeling analysis of stresses and displacements induced around engineering excavations in rock. Insitu stress. Rock failure criteria. Complete load deformation behavior of rocks. Measurement and monitoring techniques in rock mechanics. Principles of design of excavation in rocks. Analytical, numerical modeling and empirical design methods. Probabilistic and deterministic approaches to rock engineering designs. Excavation design examples for shafts, tunnels, large chambers and mine pillars. Seismic loading of structures in rock. Phenomenon of rock burst and its alleviation. One additional design project will be assigned to graduate students. Prerequisites: MNGN321. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Not Changing

**MNGN509. CONSTRUCTION ENGINEERING AND MANAGEMENT. 3.0 Semester Hrs.**
Equivalent with GOGN506,
(II) The course will provide content, methods and experience in construction planning and cost estimating, scheduling and equipment performance, contractual delivery systems and relationships, key contract clauses, risk registration and management, and project controls. Special attention will be paid to geotechnical uncertainty and risk, emerging technologies and industry trends, and to ethics and sustainability as applied to construction engineering and management practices. Co-requisites: GEGN561. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Identify all phases of a construction project from cradle to grave
- Understand the numerous roles and responsibilities of the key project players through all stages of a project, including regulatory framework
- Analyze the advantages and disadvantages of project delivery methods and select the appropriate one for a specific construction project, including environmental and social impacts
- Complete a cost estimate for a tunnel project
- Compete in a construction bid scenario
- Schedule a series of construction tasks using the critical path method
- Establish a project cash flow projection
- Identify and apply key construction contract clauses
- Identify and analyze project risks, with an accent on geotechnical risk
- Identify and assess safety and its management on underground construction projects
- Assess and manage social and ethical issues for underground construction projects

**MNGN510. FUNDAMENTALS OF MINING AND MINERAL RESOURCE DEVELOPMENT. 3.0 Semester Hrs.**
Specifically designed for non-majors, the primary focus of this course is to provide students with a fundamental understanding of how mineral resources are found, developed, mined, and ultimately reclaimed. The course will present a wide range of traditional engineering and economic topics related to: exploration and resource characterization, project feasibility, mining methods and systems, mine plant design and layout, mine operations and scheduling, labor, and environmental and safety considerations. The course will emphasize the importance of integrating social (human), political, and environmental issues into technical decision-making and design. Prerequisites: MATH111, MATH112.

**MNGN511. MINING INVESTIGATIONS. 2-4 Semester Hr.**
(I, II) Investigational problems associated with any important aspect of mining. Choice of problem is arranged between student and instructor.

Prerequisite: none. Lecture, consultation, lab, and assigned reading; 2 to 4 semester hours.

**MNGN512. SURFACE MINE DESIGN. 3.0 Semester Hrs.**
Analysis of elements of surface mine operation and design of surface mining system components with emphasis on minimization of adverse environmental impact and maximization of efficient use of mineral resources. Ore estimates, unit operations, equipment selection, final pit determinations, short- and long-range planning, road layouts, dump planning, and cost estimation. Prerequisite: MNGN210. 3 hours lecture; 3 semester hours.

**MNGN514. MINING ROBOTICS. 3.0 Semester Hrs.**
(I) Fundamentals of robotics as applied to the mining industry. The focus is on mobile robotic vehicles. Topics covered are mining applications, introduction and history of mobile robotics, sensors, including vision, problems of sensing variations in rock properties, problems of representing human knowledge in control systems, machine condition diagnostics, kinematics, and path finding. Prerequisite: CSCI404. 3 hours lecture; 3 semester hours. Offered in odd years.

**MNGN515. MINE MECHANIZATION AND AUTOMATION. 3.0 Semester Hrs.**
This course will provide an in-depth study of the current state of the art and future trends in mine mechanization and mine automation systems for both surface and underground mining, review the infrastructure required to support mine automation, and analyze the potential economic and health and safety benefits. Prerequisite: MNGN312, MNGN314, MNGN316. 2 hours lecture, 3 hours lab; 3 semester hours. Fall of odd years.

**MNGN516. UNDERGROUND MINE DESIGN. 3.0 Semester Hrs.**
Selection, design, and development of most suitable underground mining methods based upon the physical and the geological properties of mineral deposits (metallics and nonmetallics), conservation considerations, and associated environmental impacts. Reserve estimates, development and production planning, engineering drawings for development and extraction, underground haulage systems, and cost estimates. Prerequisite: MNGN210. 2 hours lecture, 3 hours lab; 3 semester hours.

**MNGN517. ADVANCED UNDERGROUND MINING. 3.0 Semester Hrs.**
(II) Review and evaluation of new developments in advanced underground mining systems to achieve improved productivity and reduced costs. The major topics covered include: mechanical excavation techniques for mine development and
production, new haulage and vertical conveyance systems, advanced ground support and roof control methods, mine automation and monitoring, new mining systems and future trends in automated, high productivity mining schemes. Prerequisite: Underground Mine Design (e.g., MNGN314). 3 hours lecture; 3 semester hours.

**MNGN518. ADVANCED BULK UNDERGROUND MINING TECHNIQUES. 3.0 Semester Hrs.**
This course will provide advanced knowledge and understanding of the current state-of-the-art in design, development, and production in underground hard rock mining using bulk-mining methods. Design and layout of sublevel caving, block caving, open stoping and blasthole stoping systems. Equipment selection, production scheduling, ventilation design, and mining costs. Prerequisites: MNGN314, MNGN516. 2 hours lecture, 3 hours lab; 3 semester hours. Spring of odd years.

**MNGN519. ADVANCED SURFACE COAL MINE DESIGN. 3.0 Semester Hrs.**
(II) Review of current manual and computer methods of reserve estimation, mine design, equipment selection, and mine planning and scheduling. Course includes design of a surface coal mine for a given case study and comparison of manual and computer results. Prerequisite: MNGN312, 316, 427. 2 hours lecture, 3 hours lab; 3 semester hours. Offered in odd years.

**MNGN520. ROCK MECHANICS IN UNDERGROUND COAL MINING. 3.0 Semester Hrs.**
(I) Rock mechanics consideration in the design of room-and-pillar, longwall, and shortwall coal mining systems. Evaluation of bump and outburst conditions and remedial measures. Methane drainage systems. Surface subsidence evaluation. Prerequisite: MNGN321. 3 hours lecture; 3 semester hours. Offered in odd years.

**MNGN521. EXTRACTIVE METALLURGY OF COPPER, GOLD AND SILVER. 3.0 Semester Hrs.**
The same as MTGN-528 Practical applications of fundamentals of chemical-processing-of-materials to the extraction of gold, silver and copper. Topics covered include: History; Ore deposits and mineralogy; Process Selection; Hydrometallurgy and leaching; Oxidation pretreatment; Purification and recovery; Refinement; Waste treatment; and Industrial examples. Prerequisite: Graduate student or senior in good standing.
**Course Learning Outcomes**

- The same as MTGN-528

**MNGN522. FLOTATION. 3.0 Semester Hrs.**
Science and engineering governing the practice of mineral concentration by flotation. Interfacial phenomena, flotation reagents, mineral-reagent interactions, and zeta-potential are covered. Flotation circuit design and evaluation as well as tailings handling are also covered. The course also includes laboratory demonstrations of some fundamental concepts. 3 hours lecture; 3 semester hours.

**MNGN523. SELECTED TOPICS. 2-4 Semester Hr.**
(I, II) Special topics in mining engineering, incorporating lectures, laboratory work or independent study, depending on needs. This course may be repeated for additional credit only if subject material is different. Prerequisite: none. 2 to 4 semester hours. Repeatable for credit under different titles.

**MNGN524. ADVANCED MINE VENTILATION. 3.0 Semester Hrs.**
(I) Advanced topics of mine ventilation including specific ventilation designs for various mining methods, ventilation numerical modeling, mine atmosphere management, mine air cooling, prevention and ventilation response to mine fires and explosions, mine dust control. Prerequisites: MNGN424 Mine Ventilation. Lecture and Lab Contact Hours: 3 hours lecture; 3 semester credit hours.

**MNGN525. INTRODUCTION TO NUMERICAL TECHNIQUES IN ROCK MECHANICS. 3.0 Semester Hrs.**
(I) Principles of stress and infinitesimal strain analysis are summarized, linear
constitutive laws and energy methods are reviewed. Continuous and laminated models of stratified rock masses are introduced. The general concepts of the boundary element and finite element methods are discussed. Emphasis is placed on the boundary element approach with displacement discontinui ties, because of its relevance to the modeling of the extraction of tabular mineral bodies and to the mobilization of faults, joints, etc. Several practical problems, selected from rock mechanics and subsidence engineering practices, are treated to demonstrate applications of the techniques. Prerequi site: MNGN321, EGGN320, or equivalent courses, MATH455. 3 hours lecture; 3 semester hours. Offered in even years.

**MNGN526. MODELING AND MEASURING IN GEOMECHANICS. 3.0 Semester Hrs.**
(II) Introduction to instruments and instrumen tation systems used for making field measurements (stress, convergence, deformation, load, etc.) in geomechanics. Techniques for determining rock mass strength and deformability. Design of field measurement programs. Interpretation of field data. Development of predictive models using field data. Intro duction to various numerical techniques (boundary element, finite element, FLAC, etc.) for modeling the behavior of rock structures. Demonstration of concepts using various case studies. Prerequisite: Graduate standing. 2 hours lecture, 3 hours lab; 3 semester hours. Offered in odd years.

**MNGN527. SOLID WASTE MINIMIZATION AND RECYCLING. 3.0 Semester Hrs.**
(II) Industrial case-studies, on the application of engineering principles to minimize waste formation and to meet solid waste recycling challenges. Proven and emerging solutions to solid waste environmental problems, especially those associated with metals. Prerequisites: ESGN500 and ESGN504.

**MNGN528. MINING GEOLOGY. 3.0 Semester Hrs.**
(I) Role of geology and the geologist in the development and production stages of a mining operation. Topics addressed: mining operation sequence, mine mapping, drilling, sampling, reserve estimation, economic evaluation, permitting, support functions. Field trips, mine mapping, data evaluation, exercises and term project. Prerequisite: GEGN401 or GEGN405. 2 hours lecture/seminar, 3 hours laboratory: 3 semester hours. Offered in even years.

**MNGN529. URANIUM MINING. 2.0 Semester Hrs.**
(I) Overview and introduction to the principles of uranium resource extraction and production. All aspects of the uranium fuel cycle are covered, including the geology of uranium, exploration for uranium deposits, mining, processing, environmental issues, and health and safety aspects. A lesser emphasis will be placed on nuclear fuel fabrication, nuclear power and waste disposal.

**MNGN530. INTRODUCTION TO MICRO COMPUTERS IN MINING. 3.0 Semester Hrs.**
(I) General overview of the use of PC based micro computers and software applications in the mining industry. Topics include the use of: database, CAD, spreadsheets, computer graphics, data acquisition, and remote communications as applied in the mining industry. Prerequisite: Any course in computer programming. 2 hours lecture, 3 hours lab; 3 semester hours.

**MNGN531. THERMODYNAMICS OF METALLURGICAL AND MATERIALS PROCESSING. 3.0 Semester Hrs.**
Application of thermodynamics to the processing of metals and materials, with emphasis on the use of thermodynamics in the development and optimization of processing systems. Focus areas will include entropy and enthalpy, reaction equilibrium, solution thermodynamics, methods for analysis and correlation of thermodynamics data, thermodynamic analysis of phase diagrams, thermodynamics of surfaces, thermodynamics of defect structures, and irreversible thermodynamics. Attention will be given to experimental methods for the measurement of thermodynamic quantities. Prerequisite: MTGN351.

**MNGN532. PARTICULATE MATERIAL PROCESSING I - COMMINUTION AND PHYSICAL SEPARATIONS. 3.0 Semester Hrs.**
An introduction to the fundamental principles and design criteria for the selection and use of standard mineral processing unit operations in comminution and physical separation. Topics covered include: crushing (jaw, cone, gyratory), grinding (ball, pebble, rod, SAG, HPGR), screening, thickening, sedimentation, filtration and hydrocyclones. Two standard mineral processing plant-design simulation software (MinOCad and JK SimMet) are used in the course. Prerequisite: Graduate or Senior in good- standing.

**MNGN533. PARTICULATE MATERIAL PROCESSING II - APPLIED SEPARATIONS. 3.0 Semester Hrs.**
An introduction to the fundamental principles and design criteria for the selection and use of standard mineral processing unit operations in applied separations. Topics covered include: photometric ore sorting, magnetic separation, dense media separation, gravity separation, electrostatic separation and flotation (surface chemistry, reagents selection, laboratory testing procedures, design and simulation). Two standard mineral processing plant-design simulation software (MinOCad and JK SimMet) are used in the course. Graduate or Senior in good-standing.

**MNGN534. ADVANCED IRON AND STEELMAKING. 3.0 Semester Hrs.**
Physicochemical principles of gas-slag-metal reactions applied to the reduction of iron ore concentrates and to the refining of liquid iron to steel. The role of these reactions in reactor design, blast furnace and direct iron smelting furnace, pneumatic steelmaking furnace, refining slags, deoxidation and degassing, ladle metallurgy, alloying, and continuous casting of steel. Prerequisites: DCGN209 or MTGN351.

**MNGN535. PYROMETALLURGICAL PROCESSES. 3.0 Semester Hrs.**
Detailed study of a selected few processes, illustrating the application of the principles of physical chemistry (both thermodynamics and kinetics) and chemical engineering (heat and mass transfer, fluid flow, plant design, fuel technology, etc.) to process development.

**MNGN536. OPERATIONS RESEARCH TECHNIQUES IN THE MINERAL INDUSTRY. 3.0 Semester Hrs.**
Analysis of exploration, mining, and metallurgy systems using statistical analysis. Monte Carlo methods, simulation, linear programming, and computer methods. Prerequisite: MNGN433. 2 hours lecture, 3 hours lab; 3 semester hours. Offered in even years.

**MNGN537. EXTRACTIVE METALLURGY OF COPPER, GOLD AND SILVER. 3.0 Semester Hrs.**
Practical applications of fundamentals of chemical-processing-of-materials to the extraction of gold, silver and copper. Topics covered include: History; Ore deposits and mineralogy; Process Selection; Hydrometallurgy and leaching; Oxidation pretreatment; Purification and recovery; Refinement; Waste treatment; and Industrial examples. Prerequisite: Graduate or Senior in good-standing.

**MNGN538. GEOSTATISTICAL ORE RESERVE ESTIMATION. 3.0 Semester Hrs.**
(I) Introduction to the application and theory of geostatistics in the mining industry. Review of elementary statistics and traditional ore reserve calculation techniques. Presentation of fundamental geostatistical concepts, including: variogram, estimation variance, block variance, kriging, geostatistical simulation. Emphasis on the practical aspects of geostatistical modeling in mining. Prerequisite: MATH323 or equivalent course in statistics; graduate or senior status.
3 hours lecture; 3 semester hours.

**MNGN539. ADVANCED MINING GEOSTATISTICS. 3.0 Semester Hrs.**
(II) Advanced study of the theory and application of geostatistics in mining engineering. Presentation of state-of-the-art geostatistical concepts, including: robust estimation, nonlinear geostatistics, disjunctive kriging, geostatistical simulation, computational aspects. This course includes presentations by many guest lecturers from the mining industry. Emphasis on the development and application of advanced geostatistical

techniques to difficult problems in the mining industry today. 3 hours lecture; 3 semester hours. Offered in odd years.

**MNGN540. CLEAN COAL TECHNOLOGY. 3.0 Semester Hrs.**
(I, II) Clean Energy - Gasification of Carbonaceous Materials - including coal, oil, gas, plastics, rubber, municipal waste and other substances. This course also covers the process of feedstock preparation, gasification, cleaning systems, and the output energy blocks along with an educational segment on CO products. These output energy blocks include feedstock to electrical power, feedstock to petroleum liquids, feedstock to pipeline quality gas. The course covers co- product development including urea, fertilizers, CO2 extraction/sequestration and chemical manufacturing.

**MNGN541. ELECTROMETALLURGY. 3.0 Semester Hrs.**
Electrochemical nature of metallurgical processes. Kinetics of electrode reactions. Electrochemical oxidation and reduction. Complex electrode reactions. Mixed potential systems. Cell design and optimization of electrometallurgical processes. Batteries and fuel cells. Some aspects of corrosion.

**MNGN542. HYDROMETALLURGY. 3.0 Semester Hrs.**
Kinetics of liquid-solid reactions. Theory of uniformly accessible surfaces. Hydrometallurgy of sulfide and oxides. Cementation and hydrogen reduction. Ion exchange and solvent extraction. Physicochemical phenomena at high pressures. Microbiological metallurgy.

**MNGN543. PRINCIPLES OF MATERIALS PROCESSING REACTOR DESIGN. 3.0 Semester Hrs.**
Review of reactor types and idealized design equations for isothermal conditions. Residence time functions for nonreacting and reacting species and its relevance to process control. Selection of reactor type for a given application. Reversible and irreversible reactions in CSTR's under nonisothermal conditions. Heat and mass transfer considerations and kinetics of gas-solid reactions applied to fluo-solids type reactors. Reactions in packed beds. Scale up and design of experiments. Brief introduction into drying, crystallization, and bacterial processes. Examples will be taken from current metallurgical practice.

**MNGN545. ROCK SLOPE ENGINEERING. 3.0 Semester Hrs.**
Introduction to the analysis and design of slopes excavated in rock. Rock mass classification and strength determinations, geological structural parameters, properties of fracture sets, data collection techniques, hydrological factors, methods of analysis of slope stability, wedge intersections, monitoring and maintenance of final pit slopes, classification of slides. Deterministic and probabilistic approaches in slope design. Remedial measures. Laboratory and field exercise in slope design. Collection of data and specimens in the field for deterring physical properties required for slope design. Application of numerical modeling and analytical techniques to slope stability determinations for hard rock and soft rock environments. Prerequisite: none. 3 hours lecture. 3 semester hours.

**MNGN546. MINE HEALTH AND SAFETY. 2.0 Semester Hrs.**
This course focuses behaviors into a culture of safety and health consciousness is a significant management challenge, particularly in the developing world. The topics include: 1) organizational culture and behavior management, 2) strategic safety planning, 3) hazard recognition, 4) root cause analysis, 5) incident management and emergency preparedness, and 6) training programs. Learning emphasis will be balanced among fundamentals, future trends and risk depending on the specific discussion topic. The frequency of training and refresher programs throughout the project life cycle will be addressed. The importance of a health and safety culture transcending the workplace through mine employees into their families, neighbors and communities will also be discussed. This is exclusively an online course that is cohort based with limited enrollment. It is offered specifically for the Professional Masters Mining Engineering and Management Program.
**Course Learning Outcomes**

- 1. Understand the importance of establishing an organization-wide culture of health and safety and will
- 2. Understand the processes and techniques for effecting changes in human behavior
- 3. Understand the elements of strategic safety planning
- 4. Understand the elements and processes for accident recognition, investigation, analysis and prevention
- 5. Understand the processes and techniques for responding to crisis and emergency situations
- 6. Understand how to design, set up and manage health and safety training programs that are tailored to specific project needs.

**MNGN547. GEOLOGY AND MINING. 3.0 Semester Hrs.**
This course focuses on how the ore deposit geology, structure, resource assessment and geochemistry are inextricably linked to major project decisions and cost control regarding mining methods and water management. The course emphasizes fundamentals of exploration, geosystem characterization, and the risks associated with failure to integrate these aspects into decision making. Major topics include: 1) ore genesis, 2) exploration methods, 3) geostatistics and resource development, 4) geologic hazards, 5) geochemistry and geo environmental considerations, 6) groundwater (further addressed in Water, Waste and Closure course), and 7) geologic factors for consideration in mine design. The importance and cost efficiency of collecting and managing data concurrent with its generation will be emphasized. This is exclusively an online course that is cohort based with limited enrollment. It is offered specifically for the Professional Masters Mining Engineering and Management Program.
**Course Learning Outcomes**

- 1. Students will describe various principal ore genesis events and relationships with local and regional geology.
- 2. Students will assess the relationship between ore deposits and mine planning activities.
- 3. Students will formulate exploration programs.
- 4. Students will formulate sampling and data validation (EDA) requirements, and identify geostatistical assessment requirements required by JORC and NI 43-101 documents.
- 5. Students will identify the parameters required to minimize risks associated with geological structures, resource evaluation and mine planning.

**MNGN548. INFORMATION TECHNOLOGIES FOR MINING SYSTEMS. 3.0 Semester Hrs.**
This course will focus on the role of information systems (IS) for specific mining systems in the mine life cycle. We will look at various data sources and acquisition methods like internet-of-things, crowdsourcing, and blockchain. Management of data is the principal function of an IS, so we will look at the main features and functions of a database management system (DBMS). Due to the exponential growth of unstructured data, the integration of structured data sets managed in a DBMS with big data infrastructures, which are mainly unstructured, and will be another focus of the course. Geographic Information Systems (GIS) will be introduced for managing spatial and tabular data. Advancements in sensor technologies allow the various remote sensing (RS) products to be integrated with GIS in various mining systems. The fundamental principles of design visualizations will also be explored. The IS in various

full/semi-autonomous mining systems will be covered, and we will analyze the methods of interoperability and related infrastructures. We will identify cybersecurity issues related to autonomous mining systems and future trends. This is exclusively an online course that is cohort based with limited enrollment. It is offered specifically for the Professional Masters - Mining Engineering and Management Program.

**Course Learning Outcomes**

- 1. Students will design and evaluate mining support facilities, and utilities.
- 2. Students will design top-level communication, control and monitoring systems.
- 3. Students will construct mine operations databases, perform queries, and evaluate outcomes.
- 4. Students will evaluate mine plant systems for cost, environmental compliance, risk, and life-of-project sustainability.
- 5. Students will formulate, evaluate, and present design alternatives for a mine plant project.

**MNGN549. MARINE MINING SYSTEMS. 3.0 Semester Hrs.**
(I) Define interdisciplinary marine mining systems and operational requirements for the exploration survey, sea floor mining, hoisting, and transport. Describe and design components of deep-ocean, manganese-nodule mining systems and other marine mineral extraction methods. Analyze dynamics and remote control of the marine mining systems interactions and system components. Describe the current state-of-the-art technology, operational practice, trade-offs of the system design and risk. Prerequisite: EGGN351, EGGN320, GEOC408. 3 hours lecture; 3 semester hours. Offered alternate even years.

**MNGN550. NEW TECHNIQUES IN MINING. 3.0 Semester Hrs.**
(II) Review of various experimental mining procedures, including a critical evaluation of their potential applications. Mining methods covered include deep sea nodule mining, in situ gassification of coal, in situ retorting of oil shale, solution mining of soluble minerals, in situ leaching of metals, geothermal power generation, oil mining, nuclear fragmentation, slope caving, electro-thermal rock penetration and fragmentation. Prerequisite: Graduate standing. 3 hours lecture; 3 semester hours. Offered in even years.

**MNGN551. MINE ACCOUNTING. 2.0 Semester Hrs.**
Accounting is the process of recording business transactions. Financial analysis uses accounting information to gain insights into the financial position, performance, and prospects of a company. This course aims at building the accounting and financial knowledge and skills to allow students to participate in decision-making, financial, and corporate management processes. The objective is to make better managers and leaders by developing practical knowledge and abilities to interpret financial statements, evaluate a competitive position from the financial perspective, and determine the financial implications of business decisions. This is exclusively an online course that is cohort-based with limited enrollment. It is offered specifically for the Professional Masters Program in Mining Engineering and Management.

**Course Learning Outcomes**

- 1. Students will be knowledgeable of principles of accounting as applicable to engineers and managers in the mining industry.
- 2. Students will understand and be able to evaluate financial statements and balance sheets.
- 3. Students will understand the application of cost accounting methods for mine projects and operations including the proper application of accruals.
- 4. Students will understand accounting standards in the U.S. and internationally from a managerial perspective.
- 5. Students will be aware of mandatory financial reporting requirements for corporate entities in the U.S.

**MNGN552. SOLUTION MINING AND PROCESSING OF ORES. 3.0 Semester Hrs.**
(II) Theory and application of advanced methods of extracting and processing of minerals, underground or in situ, to recover solutions and concentrates of value-materials, by minimization of the traditional surface processing and disposal of tailings to minimize environmental impacts. Prerequisite: Senior or graduate status. 3 hours lecture, 3 semester hours. Offered in spring.

**MNGN553. MINE DESIGN AND OPERATION PLANNING. 3.0 Semester Hrs.**
This course provides an overview of mine design and operations fundamentals with a focus on the future trends which considers where the industry will be in the next decade(s). Topics give an over-arching significance to social, environmental, health and safety considerations in traditional design and operations decision-making. Principal topics will include 1) mining methods and planning, 2) production scheduling and optimization, 3) robotics and automation, 4) equipment capabilities and selection processes, 5) mine ventilation, 6) rock mechanics and ground control, and 7) waste disposal (high level, further addressed in Water, Waste and Closure course). Project life cycle and sustainability principles will be applied throughout the course content. This is exclusively an online course that is cohort based with limited enrollment. It is offered specifically for the Professional Masters Mining Engineering and Management Program.

**Course Learning Outcomes**

- 1. Students will specify underground and surface mining methods that can optimally exploit a mineral resource based on its chemical and physical characteristics.
- 2. Students will prepare mine production schedules that can provide desired cash flows based on ore production and waste disposal.
- 3. Students will evaluate emerging technologies to improve health and safety, and improve productivity.
- 4. Students will design mine ventilation plans to effectively provide the desired working atmosphere.
- 5. Students will characterize local geological conditions to design a ground control plan.
- 6. Students will develop a sustainable waste disposal plan to comply with government regulations and social concerns.
- 7. Students will assess risks and develop plans to mitigate and manage risks.

**MNGN554. MINE FINANCE. 2.0 Semester Hrs.**
This course describes the finance principles applicable to the mining industry. It addresses the practical application of these principles to a level of detail appropriate for a manager or corporate executive to understand what it takes to raise money in the international marketplace to finance a corporate entity or a specific mining project. This is exclusively an online course that is cohort-based with limited enrollment. It is offered specifically for the Professional Masters Program in Mining Engineering and Management.

**Course Learning Outcomes**

- 1. Students will be knowledgeable of principles of finance as applicable to engineers and managers in the mining industry.

- 2. Students will be aware and understand various financing methods for establishing corporate equity and for funding specific mine projects.
- 3. Students will understand the fundamentals of asset and cash management in a mining venture.
- 4. Students will be aware of approaches and challenges of mergers and acquisitions.
- 5. Students will be aware of the financial challenges and potential remedies throughout the mine life cycle from exploration to closure.
- 6. Students will know how to apply financial ratios in analyzing a mining company's financial health.
- 7. Students will be aware of the purposes and protocols for audits.

**MNGN555. MINE INVESTMENT EVALUATION. 3.0 Semester Hrs.**
This course discusses the elements, methods and analyses required to evaluate the viability and robustness of a mining project. Current practices for introducing the uncertain nature of most of the important variables in an investment analysis are addressed. While future trends and risks will be covered, course emphasis will be on the fundamentals of determining the feasibility of a project and the elements contained in a robust financial model to demonstrate that feasibility. Topics include: 1) laws and security exchange expectations for publicly disclosed documents, 2) feasibility study content, 3) responsibilities of the Qualified Person, 4) capital and operating cost estimation, 5) accruals and taxes, 6) financial analysis and cash flow modeling, 7) sensitivity analysis, and 8) public reporting. This is exclusively an online course that is cohort based with limited enrollment. It is offered specifically for the Professional Masters Mining Engineering and Management Program.
**Course Learning Outcomes**

- 1. Students acquire an advanced knowledge in mine capital investment evaluation utilizing time value of money principles.
- 2. Students are knowledgeable of implications on capital investments of tax policy, sustainability requirements, leasing, debt financing and other forms of capital structure in a project.
- 3. Students acquire knowledge for performing cost estimation for capital and operating cost budgets in feasibility studies.
- 4. Students are knowledgeable of how to prepare and the requirements for feasibility studies at the different levels of detail.
- 5. Students will be aware of world standards for public reporting requirements of mineral resources, reserves and investments.
- 6. Students are knowledgeable of methods of sensitivity and real options evaluation of capital investments.

**MNGN556. MINE WATER AND ENVIRONMENT. 3.0 Semester Hrs.**
Equivalent with CEEN556,
(I) This course will cover core aspects of mine water and mining geotechnics. The main topics to be covered relate to surface and groundwater flow along open pits and underground excavations, tailings and impoundments, mine spoils and waste rock, reclamation and closure. Course emphasizes leadership, teamwork, communication, and creative problem solving skills through the use of case examples, homework, and exams which emphasize typical water and geotechnical problems relevant to the mining industry. Prerequisite: CHGN121, CHGN122. 3 hours lecture, 3 semester hours.
**Course Learning Outcomes**

- Predict physical characteristics of a hydrogeological system
- Construct conceptual models of the hydrogeological conditions in a mine setting
- Propose effective methods for management of an abandoned mine
- Describe requirements for mine closure and reclamation

**MNGN557. MINERAL ECONOMICS AND POLICY. 2.0 Semester Hrs.**
This course is designed to help students learn some of the basic economic principles that will help them better understand mineral commodity market behavior and the important factors that drive mineral supply, demand, prices and other market elements. The course is designed to help you build the economic, market and policy knowledge and skills to effectively participate in company decision-making and strategic management discussions. It concentrates on the economic factors and principles that mine managers and executives need to recognize, analyze and deal with in order to position their company for long-term success in volatile commodity markets. The overall objective of this course is not to make students mineral economists, but to make them a better managers and leaders by developing a practical understanding of the commodity markets in which they will deal. It will also give them a deeper knowledge of government's perspective and role in the mineral industry. This is exclusively an online course that is cohort based with limited enrollment. It is offered specifically for the Professional Masters Mining Engineering and Management Program.
**Course Learning Outcomes**

- 1. Students will be knowledgeable of the underlying mineral market dynamics of supply and demand.
- 2. Students will be aware of historical and potential factors that influence the demand and supply of minerals.
- 3. Students will understand the role of public policy in defining the mining industry in a nation including the requirements for tax and royalty revenue, economic contributions and sustainable development of the local and greater communities.

**MNGN558. MINERAL PROCESSING. 3.0 Semester Hrs.**
This course addresses the fundamentals for developing an appropriate and cost-efficient mineral process for a given ore type and the risks that factor into deploying the selected process. Consideration will be given for the need to demonstrate a proven and robust process to potential investors (a bankable process). Topics will include 1) unit operations and material handling, 2) sampling techniques specific to process considerations, 3) material testing and data organization and management, 4) water and energy considerations, 5) mill design and development (concept through construction), and 6) process waste disposal (high level, further addressed in Water, Waste and Closure course). Timing of process design within the project life cycle will be addressed. This is exclusively an online course that is cohort based with limited enrollment. It is offered specifically for the Professional Masters Mining Engineering and Management Program.
**Course Learning Outcomes**

- 1. Students will identify and specify mill unit operations that are appropriate for a given ore.
- 2. Students will establish project develop plans from concept through operation.
- 3. Students will estimate the capital and operating cost of mills.
- 4. Students will develop an economic model from concentrate qualities and smelter schedules.
- 5. Students will assess risks and emerging trends in mineral processing systems.
- 6. Students devise mill performance testing programs.
- 7. Students will construct water and energy management plans.

**MNGN559. MECHANICS OF PARTICULATE MEDIA. 3.0 Semester Hrs.**
(1) This course allows students to establish fundamental knowledge of quasi-static and dynamic particle behavior that is beneficial to interdisciplinary material handling processes in the chemical, civil, materials, metallurgy, geophysics, physics, and mining engineering. Issues of interst are the definition of particl size and size distribution, particle shape, nature of packing, quasi-static behavior under different external loading, particle collisions, kinetic theoretical modeling of particulate flows, molecular dynamic simulations, and a brief introduction of solid-fluid two-phase flows. Prerequisite: none. 3 hours lecture; 3 semester hours. Fall semesters, every other year.

**MNGN560. INDUSTRIAL MINERALS PRODUCTION. 3.0 Semester Hrs.**
This course describes the engineering principles and practices associated with quarry mining operations related to the cement and aggregate industries. The course will cover resource definition, quarry planning and design, extraction, and processing of minerals for cement and aggregate production. Permitting issues and reclamation, particle sizing and environmental practices, will be studied in depth.

**MNGN561. PROJECT MANAGEMENT. 3.0 Semester Hrs.**
This course addresses the many aspects of business and project management. As the business environment changes, mine managers and executives face competing pressures to deliver both profits and effective social, environmental and economic results. Leadership is a fundamental tool for the effective executive. While a solid base of technical and operational skills is required, they must also engage a workforce, build and retain employees and seize opportunities for growth and development. While the course will address future trends and risks, emphasis will be on the fundamentals of effective business and project management. Topics include: 1) leadership, 2) project planning and controls, 3) quality assurance, 4) business process improvement, 5) risk assessment techniques, 6) personnel management and 7) conflict resolution. Because the leadership role is one that goes beyond the workplace, the course will explore the role of the project manager in communications and supporting sustainable investments. This is exclusively an online course that is cohort based with limited enrollment. It is offered specifically for the Professional Masters Mining Engineering and Management Program. Prerequisites: MATH225 and MTGN461 or equivalent.
**Course Learning Outcomes**

- 1. Students are knowledgeable of all aspects of project management from major mine construction projects to business improvement projects.
- 2. Students are capable of applying improvement tools to boost business results.
- 3. Students are adept at methods for analyzing and managing risk.
- 4. Students understand methods to improve decision-making under conditions of uncertainty.
- 5. Students are capable of applying constraints analysis and using methods to optimize mine systems and processes.
- 6. Students understand when and how to apply various approaches for conflict resolution in the business.

**MNGN562. MINING ENVIRONMENTAL AND SOCIAL RESPONSIBILITY. 2.0 Semester Hrs.**
This course explores the fundamentals of, and to the extent relevant, the future trends in building environmentally and socially responsible mining projects in the context of the project life cycle. Emphasis will be on 1) host country and international industry regulatory expectations and good practice; 2) communication strategies, stakeholder engagement, and building community support; 3) mining project screening and scoping, 4) characterization of environmental and social media; 5) predicting project-induced environmental and social impacts and identifying plausible mitigating actions to reduce adverse impacts to acceptable levels and enhance project benefits; and 6) developing and implementing effective social and environmental management systems. Course emphasis will be on executing these fundamentals adequately and in a culturally appropriate manner, and on the risk to project continuity and corporate reputation if these fundamentals are mishandled. This is exclusively an online course that is cohort based with limited enrollment. It is offered specifically for the Professional Masters Mining Engineering and Management Program.
**Course Learning Outcomes**

- 1. Understand the significance and commonalities of the administrative and regulatory framework in host country jurisdictions and the importance of industry good practices, lender and development bank expectations.
- 2. Understand the fundamentals of the environmental and social assessment process and how it fits into the overall project cycle.
- 3. Understand the business case for social and environmental assessment, including key concepts and the roles and responsibilities of assessment professionals.
- 4. Understand what goes into each procedural step of the assessment process.
- 5. Understand how to limit the scale of the assessment to address only what is needed, no more and no less, so that the resulting environmental and social assessment is cost-efficient, appropriately scaled and fit-for-purpose.
- 6. Understand the need and processes for stakeholder engagement and how it fits with the social and environmental assessment process throughout the project cycle.
- 7. Understand the business case for stakeholder engagement and the roles and responsibilities of assessment professionals.
- 8. Understand the elements of, and continuous improvement processes for, a comprehensive environmental and social management system.

**MNGN563. WATER WASTE AND MINE CLOSURE. 3.0 Semester Hrs.**
This course addresses three disciplines that are critically important to a successful and sustainable mining project. Beyond the ore deposit, water is essential for all mining projects. Supplies must be balanced among local and regional water users. Closure and reclamation is one phase of the mine life cycle and constitutes a significant mitigating action and cost to mining projects. The course will address fundamentals and future trends, but significant emphasis will be placed on the environmental, social, and cost control risks. Topics covered include: 1) water supply, disposal and treatment, 2) site-wide water management, 3) mine waste rock management, 4) process waste and tailings management, 5) solid, hazardous and medical waste minimization, recycling and disposal, 6) closure design (conceptual to construction-ready), 7) surety estimation and available surety instruments, and 8) post-closure elements including monitoring, maintenance, retrenchment, close-out costs and surety release. The importance of effective water and waste management practices, as well as integrating closure planning techniques into engineering designs, will be stressed throughout the project life cycle. This is exclusively an online course that is cohort based with limited enrollment. It is offered specifically for the Professional Masters Mining Engineering and Management Program.

**Course Learning Outcomes**

- 1. Understand the fundamentals of watershed hydrology and hydrometeorology at mine sites 2. Understand the fundamentals of hydrogeology, including aquifer properties, saturated and unsaturated flow and groundwater quality. 3. Understand mining hydrogeology, mine dewatering systems and the development of the water supply 4. Understand surface water management, sedimentation control and surface water models 5. Understand water balances and models, including facility-specific water balances (e.g., tailings, heap leach facilities) and site-wide water balances 6. Understand hydrology at closure, including pit lakes, underground reservoirs and water treatment 7. Understand the risks associated with mismanagement of mine wastes 8. Understand the applicable guidelines and regulatory framework pertaining to mine wastes. 9. Understand the elements of material characterization, including physical and geochemical characterization 10. Understand the methods and design criteria for heap leaching systems and for the permanent storage of mine waste rock and mill tailings 11. Understand the fundamentals of solid, hazardous and medical waste management 12. Understand slope stability evaluations as they relate to mine waste and closure scenarios 13. Understand the fundamentals of mine closure planning, design and implementation as well as the financial implications

**MNGN565. MINE RISK MANAGEMENT. 3.0 Semester Hrs.**
(II) Fundamentals of identifying, analyzing, assessing and treating risks associated with the feasibility, development and operation of mines. Methodologies for identifying, assessing and treating risks will be presented and practiced in case studies and exercises. Concepts and principles for analyzing risks will be demonstrated and practiced utilizing deterministic and stochastic models, deductive models, decision trees and other applicable principles. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- At the conclusion of the class students will… a) Be aware of the types of risks associated with the mining industry b) Be knowledgeable of the systematic risk management process – identification, analysis, assessment and treatment c) Be familiar with concepts and methods used in risk identification, analysis, assessment and treatment d) Be familiar with techniques applied in causative analysis e) Be familiar with quantitative risk analysis methods as applied to the mining industry – decision trees, stochastic modeling, deductive modeling and other applicable principles

**MNGN566. INNOV8X. 3.0 Semester Hrs.**
Innov8x introduces concepts and tools to accelerate the design, validation and adoption of innovations in support of creative problem solving. Using an entrepreneurial mindset, we learn how to identify and frame problems that beneficiaries and stakeholders face. We attempt to design and test practical solutions to those problems in collaboration with those who experience the problems. We apply beneficiary discovery, pretotyping, business model design (social, economic and environmental), constrained creativity, efficient experimentation, and rapid iteration. While resolving challenges involves technical solutions, an important aspect of this course is directly engaging beneficiaries and stakeholders in social contexts to develop solutions with strong impact potential. Innov8x is grounded in collaborative creativity theory at the intersection of organizational behavior (social psychology), design principles, entrepreneurship and innovation management.
**Course Learning Outcomes**

- Frame and translate complex ambiguous problems in resources sciences and engineering into actionable opportunities for innovation
- Conduct effective, objective and ongoing beneficiary discovery in efficient ways
- Combine tools and methods to quickly test assumptions and secure beneficiary acceptance
- Develop creative approaches to navigate real and perceived constraints
- Leverage mentor and stakeholder support through credible communication based on research
- Launch innovative solutions with the advocacy of beneficiaries and stakeholders
- Create value by solving complex sociotechnical problems with scientific and technical foundations

**MNGN567. SUSTAINABLE DEVELOPMENT AND EARTH RESOURCES. 3.0 Semester Hrs.**
(II) Earth resource industries are increasingly being called on to contribute to sustainable development in the communities and regions in which they take place. In this graduate level course, students will develop an understanding and appreciation of the ways in which resource extraction projects can contribute to sustainable development. The course will be framed around the UN Sustainable Development Goals and will include the following elements: 1) examination of sustainable development principles relevant to mining and energy projects and current best practices and continuing challenges; 2) critical assessment of necessary elements of corporate social responsibility policies and practices; 3) evaluation of stakeholder roles and specify strategies for effective stakeholder engagement; 4) identification of criteria for engineering and management that contribute to sustainable development; and 5) evaluation of real cases that demonstrate where social license to operate was either gained/maintained or not granted/withdrawn. 2 hours lecture; 3 hours lab; 3 hours total.
**Course Learning Outcomes**

- Demonstrate knowledge of sustainable development principles relevant to mining and energy projects and identify current best practices and continuing challenges.
- Critically evaluate necessary elements of Corporate Social Responsibility concepts and practices (transparency, accountability, continuous improvement, etc.).
- Determine stakeholder roles in general and for particular projects, and specify strategies for effective stakeholder engagement
- Specify criteria for engineering projects that contribute to sustainable development, and evaluate the “business case” for incorporating such criteria.
- Identify mine management successes in real cases where a social license to operate was gained/maintained, or “fatal flaws” in cases where a social license was not granted/withdrawn; and suggest alternative approaches in unfavorable cases.

**MNGN570. SAFETY AND HEALTH MANAGEMENT IN THE MINING INDUSTRY. 3.0 Semester Hrs.**
(I) Fundamentals of managing occupational safety and health at a mining operation. Includes tracking of accident and injury statistics, risk management, developing a safety and health management plan, meeting MSHA regulatory requirements, training, safety audits and accident investigations. 3 hours lecture; 3 semester hours.

**MNGN571. ENERGY, NATURAL RESOURCES, AND SOCIETY. 3.0 Semester Hrs.**
(I) This is a graduate course that applies a social science lens to understanding the intersections between energy and mineral

developments and communities. In this seminar-style course, we will examine these intersections through a case study approach that includes directed readings, such as ethnographies and peer-reviewed journal articles, and that incorporates student-led discussions and research projects. By exploring various development initiatives, such as oil and gas, mining, wind, solar, nuclear, and hydropower, students will gain a comprehensive understanding of the energy-mineral-society nexus and the role communities play in both furthering and limiting these developments. 3 hours lecture; 3 semester hours.

**Course Learning Outcomes**

- Apply critical thinking and interdisciplinary analyses to the relationship between energy and mineral developments and society.
- Research, write about, present, and discuss case studies on the relationship among energy, natural resources, and society in a variety of contexts
- Apply concepts such as, sustainability, community development, corporate social responsibility, and social license to operate to analyses of the energy-natural resources-society nexus

**MNGN572A. MINING INDUSTRY MANAGEMENT CAPSTONE DESIGN. 0.5 Semester Hrs.**

This is the first of a three-course series to design, develop and deliver a project that will ideally be of value to the student's employer in his or her current role in the company. The project will be created and done independently by the student, typically in conjunction with his or her existing job. Prerequisite: None Co-requisite: None.

**Course Learning Outcomes**

**MNGN572B. MINING INDUSTRY MANAGEMENT CAPSTONE DEVELOPMENT. 0.5 Semester Hrs.**

This is the second of a three-course series to design, develop and deliver a project that will ideally be of value to the student's employer in his or her current role in the company. The project will be created and done independently by the student, typically in conjunction with his or her existing job. Prerequisite: MNGN571A.

**Course Learning Outcomes**

- Ability to think through, define and design a project with sufficient detail to allow for detailed project planning and development. Evaluate and communicate clearly a written response to a request for proposal (RFP) from the perspective of a contractor or consultant that encompasses contractor background, project scope and content and a detailed schedule, budget, milestone deliverables, and tasks necessary to complete the project to address client needs. Craft a response to an RFP with specific sensitivity to the target audience and their needs and objectives and also serves as an effective marketing document for contractor/consultant expertise and experience

**MNGN572C. MINING INDUSTRY MANAGEMENT CAPSTONE DELIVERY - FINAL SECTION. 1.0 Semester Hr.**

This is the final course of a three-course series to design, develop and deliver a project that will ideally be of value to the student's employer in his or her current role in the company. The project will be created and done independently by the student, typically in conjunction with his or her existing job. Prerequisite: MNGN572B.

**Course Learning Outcomes**

**MNGN575. HEAT MINING. 3.0 Semester Hrs.**

(I) Heat Mining focuses on identifying available sub-surface heat sources. Heat trapped in crystalline rock deep underground is available by engineering an artificial geothermal system. Hot geothermal fluid, heat generated by underground coal fire and hot water trapped in abandoned underground mine are some of other examples. We will discuss how to find them, how to estimate them, and how to extract and convert them to a usable energy form. The concept of sustainable resource development will be taught as the foundation of heat mining. Prerequisites: None. 3 hours lecture; 3 semester hours.

**Course Learning Outcomes**

- The following outcomes are expected: understanding of the concept of sustainable heat mining; understanding the state-of-the-art heat recovery and utilization methods; understanding stakeholders

**MNGN581. FUNDAMENTALS OF TAILINGS ENGINEERING I. 3.0 Semester Hrs.**

This course provides a broad overview of tailings storage facility (TSF) operation and governance. Topics covered include mineral processing and tailings generation (volume vs. commodity produced; tailings physical, mineralogical, and geochemical) characterization; tailings continuum and rheology (including solid-liquid separation, dewatering, thickening, and filtering); introduction to tailings geotechnics; TSF Design and Operations; tailings innovations in the mining industry. Prerequisite: BSc in Mining Engineering, Geosciences, or related fields.

**Course Learning Outcomes**

- Describe the process in which tailings are generated from ore processing, and contrast tailings production from different mines as a function of commodity;
- Distinguish and compare different types of tailings in terms of physical and chemical/mineralogical characteristics, and develop a logical argument based on the concepts of tailings generation to explain the differences;
- Differentiate tailings based on the rheology of the "tailings continuum" and explain how the factors affecting yield strength and viscosity impact on tailings management;
- Analyze the different technologies applied for water reduction in the context of tailings dewatering, thickening, and filtering;
- Contrast current practices in mine tailings to identify challenges that are pushing innovation in the industry, including demands for tailings minimization, environmental and social impacts, and governance (ESG);
- Explain the importance of integrating the existing mine workings into planning and siting of a tailings facility;
- Apply data / information sources to design an effective site investigation.
- Apply material balance and water balance analysis to TSF initial design, and identify and assess external considerations that influence siting;
- Apply multiple accounts analysis to assess candidate locations for a future tailings facility;
- Design an effective surveillance and monitoring program considering the outcomes from geotechnical investigations;
- Discuss strength and deformation of tailings with emphasis on drained and undrained shear behavior, and describe importance of and methods used for evaluating dilative/contractive and brittle/ductile behavior;
- Describe a framework to connect stress, density, water pressures and shear behavior, and identify common loading conditions in tailings facilities, and identify critical design cross sections; and,

- Apply several methods of geotechnical analyses to evaluate the stability and performance of TSFs.

**MNGN582. FUNDAMENTALS OF TAILINGS ENGINEERING II. 3.0 Semester Hrs.**
This course provides a framework for engineering design and decisions regarding tailings storage facility (TSF) water systems, multi-stakeholder risk management and operations, and TSF closure. Topics covered include TSF Water Management, TSF Operations and Compliance and TSF Closure and Reclamation. Prerequisite: BSc in Mining Engineering, Civil Engineering, Geosciences or related engineering fields.
**Course Learning Outcomes**

- Define the role of water in the planning and operation of a TSF.
- Describe the hydrologic processes important to surface water, seepage and groundwater management at TSFs.
- Understand the current practice of addressing climate uncertainty and climate change.
- Analyze the role of the mine water management plan in TSF management and decision making.
- Explain what water balance models are, how they can be used to improve decision making, and what techniques can be implemented to improve model reliability.
- Describe the essential components, risks and generally accepted risk mitigation for the design and operation of TSF water management systems.
- Provide perspective on project management aspects of tailings construction, including managing construction contractors, resident engineering, quality assurance and quality control, and documentation
- Manage development and implementation of an OMS (Operation, Maintenance and Surveillance) systems
- Manage the process of developing EAP (Emergency Action Plans; called Emergency Preparedness and Response Plans in the Global Industry Standard
- Explain and implement applicable international standards of care, including the Global Tailings Standard, the Mining Association of Canada (MAC) guidelines, The Canadian Dam Association (CDA) guidelines and other related references
- Describe the process and components of TSF decommissioning and closure.
- Compare and contrast techniques for minimizing TSF closure challenges via closure-oriented tailings management through life-of-mine.
- Select components and design different cover types for function.
- Prepare closure cost estimates and schedules.
- Compare financial assurance instruments.
- Distinguish between net present value and whole-of-life accounting.
- Develop a TSF closure plan that fits within an integrated site-wide closure plan.

**MNGN585. MINING ECONOMICS. 3.0 Semester Hrs.**
(I) Advanced study in mine valuation with emphasis on revenue and cost aspects.
Topics include price and contract consideration in coal, metal and other commodities; mine capital and operating cost estimation and indexing; and other topics of current interest. Prerequisite: MNGN427 or EBGN504 or equivalent. 3 hours lecture; 3 semester hours. Offered in even years.

**MNGN590. MECHANICAL EXCAVATION IN MINING. 3.0 Semester Hrs.**
(II) This course provides a comprehensive review of the existing and emerging mechanical excavation technologies for mine development and production in surface and underground mining. The major topics covered in the course include: history and development of mechanical excavators, theory and principles of mechanical rock fragmentation, design and performance of rock cutting tools, design and operational characteristics of mechanical excavators (e.g. continuous miners, roadheaders, tunnel boring machines, raise drills, shaft borers, impact miners, slotters), applications to mine development and production, performance prediction and geotechnical investigations, costs versus conventional methods, new mine designs for applying mechanical excavators, case histories, future trends and anticipated developments and novel rock fragmentation methods including water jets, lasers, microwaves, electron beams, penetrators, electrical discharge and sonic rock breakers. Prerequisite: Senior or graduate status. 3 hours lecture; 3 semester hours. Offered in odd years.

**MNGN598. SPECIAL TOPICS IN MINING ENGINEERING. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**MNGN598. SPECIAL TOPICS. 1-6 Semester Hr.**

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**MNGN599. INDEPENDENT STUDY IN MINING ENGINEERING. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**MNGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

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**MNGN625. GRADUATE MINING SEMINAR. 1.0 Semester Hr.**
(I, II) Discussions presented by graduate students, staff, and visiting lecturers on research and development topics of general interest. Required of all graduate students in mining engineering every semester during residence.

**MNGN631. TRANSPORT PHENOMENA IN METALLURGICAL AND MATERIALS SYSTEMS. 3.0 Semester Hrs.**
Physical principles of mass, momentum, and energy transport. Application to the analysis of extraction metallurgy and other physicochemical processes.

**MNGN698. SPECIAL TOPICS IN MINING ENGINEERING. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**MNGN699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**MNGN699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**MNGN699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**MNGN700. GRADUATE ENGINEERING REPORTMASTER OF ENGINEERING. 1-6 Semester Hr.**
(I, II) Laboratory, field, and library work for the Master of Engineering report under supervision of the student’s advisory committee. Required of candidates for the degree of Master of Engineering. Variable 1 to 6 hours. Repeatable for credit to a maximum of 6 hours.

**MNGN707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.**
(I, II, S) Research credit hours required for completion of a Masters-level thesis or Doctoral dissertation. Research must be carried out under the direct supervision of the student's faculty advisor. Variable class and semester hours. Repeatable for credit.

## Department Head

Bill Zisch

## Associate Department Head

H. Sebnem Duzgun

## Professors

Corby Anderson

Kadri Dagdelen

H. Sebnem Düzgün

Linda Figueroa

Priscilla P. Nelson

Jamal Rostami

## Associate Professors

Veronica Eliasson

Elizabeth Holley

Rennie Kaunda

Jaeheon Lee

Hugh B. Miller

Nicole Smith

Gabriel Walton

## Teaching Assistant Professor

Heather Lammers

## Professors of Practice

George Sturgis

## Research Professor

D. Erik Spiller

## Research Assistant Professor

Aaron Malone

# Petroleum Engineering

## Degrees Offered

- Master of Engineering in Petroleum Engineering
- Master of Science in Petroleum Engineering
- Doctor of Philosophy in Petroleum Engineering

## Program Description

The department offers a choice of a master of science (MS) degree or a master of engineering (ME) degree. For the MS degree, a thesis is required in addition to course work. For the ME degree, no thesis is required, but the coursework requirement is greater than that for the MS degree. The Petroleum Engineering Department also offers Petroleum

Engineering (PE) undergraduate students the option of a Combined Undergraduate/Graduate Program. This is an accelerated program that provides the opportunity for PE students to get a head start on their graduate education.

Applications from students with an MS in Petroleum Engineering, or in another complimentary discipline, will be considered for admission to the doctor of philosophy (PhD) program. To obtain the PhD degree, a student must demonstrate unusual competence, creativity, and dedication in the degree field. In addition to extensive course work, a dissertation is required for the PhD degree.

## Applying for Admission

All graduate applicants must have taken core engineering, math and science courses before applying to graduate school. For Colorado School of Mines this would be 3 units of Calculus, 2 units of Chemistry with Quantitative Lab, 2 units of Physics, Differential Equations, Statics, Fluid Mechanics, Thermodynamics and Mechanics of Materials. To apply for admission, follow the procedure outlined in the general section of this catalog. Three letters of recommendation must accompany the application. The Petroleum Engineering Department requires the general test of the Graduate Record Examination (GRE) for applicants to all degree levels.

Applicants for the Master of Science and Master of Engineering programs should have a minimum score of 155 or better, and applicants for the PhD program are expected to have 159 or better on the quantitative section of the GRE exam, in addition to acceptable scores in the verbal and analytical sections. The GPA of the applicant must be 3.0 or higher. The graduate application review committee determines minimum requirements accordingly, and these requirements may change depending on the application pool for the particular semester. The applicants whose native language is not English are also expected to provide satisfactory scores on the TOEFL (Test of English as a Foreign Language) exam as specified in the general section of this catalog.

## Required Curriculum

A student in the graduate program selects course work by consultation with the faculty advisor and with the approval of the graduate committee. Course work is tailored to the needs and interests of the student. Students who do not have a BS degree in petroleum engineering must take deficiency courses as required by the department as soon as possible in their graduate programs. Depending on the applicant's undergraduate degree, various basic undergraduate petroleum engineering and geology courses will be required. These deficiency courses are not counted toward the graduate degree; nonetheless, the student is expected to pass the required courses and the grades received in these courses are included in the GPA. Not passing these courses can jeopardize the student's continuance in the graduate program. It is desirable for students with deficiencies to complete the deficiencies or coursework within the first two semesters of arrival to the program or as soon as possible with the approval of their advisor.

All PE graduate students are required to complete 3 credit hours of course work in writing, research, or presentation intensive classes, such as SYGN683, SYGN684, PEGN681 LICM501, SYGN501, and SYGN600, as agreed to by their graduate advisor.

## Fields of Research

Current fields of research include:

- Petroleum data analytics
- Artificial Intelligence applications to porous media
- Rock and fluid properties, phase behavior, and rock mechanics
- Geomechanics
- Formation evaluation, well test analysis, and reservoir characterization
- Oil recovery processes
- IOR/EOR Methods
- Naturally fractured reservoirs
- Analytical and numerical modeling of fluid flow in porous media
- Pore-scale modeling and flow in nanopores
- Development of unconventional oil and gas plays
- Geothermal energy
- Gas hydrates
- Completion and stimulation of wells
- Horizontal and multilateral wells
- Multistage fracturing of horizontal wells
- Drilling management and rig automation
- Fluid flow in wellbores and artificial lift
- Drilling mechanics
- Carbon sequestration and storage
- Environment, health, and safety in oil and gas industry

Research projects may involve professors and graduate students from other disciplines. Projects may include off-campus laboratories, institutes, and other resources.

The Petroleum Engineering Department houses a research institute, a research center, and two consortia.

## Research Institute

- Unconventional Natural Gas and Oil Institute (UNGI)

## Research Center

- Marathon Center of Excellence for Reservoir Studies (MCERS)

## Research Consortia

- Fracturing, Acidizing, Stimulation Technology (FAST) Consortium
- Unconventional Reservoir Engineering Project (UREP) Consortium

## Special Features

In the exchange programs with the Petroleum Engineering Departments of the Mining University of Leoben, Austria, Technical University in Delft, Holland, and King Fahd University of Petroleum Minerals (KFUPM) in Dhahran, Saudi Arabia, a student may spend one semester abroad during graduate studies and receive full transfer of credit back to Colorado School of Mines with prior approval of the Petroleum Engineering Department at Colorado School of Mines.

Marquez Hall is home to the Petroleum Engineering Department. A prominent campus landmark, Marquez Hall showcases Mines' long-standing strengths in its core focus areas and our commitment to staying at the forefront of innovation. The building is designed using aggressive energy-saving strategies and is LEED certified. Marquez Hall is the first building on Colorado School of Mines Campus that is funded entirely by donations.

The Petroleum Engineering Department enjoys strong collaboration with the Geology and Geological Engineering Department and Geophysics Department at Colorado School of Mines. Courses that integrate the faculty and interests of the three departments are taught at the graduate levels.

The department is close to oil and gas field operations, oil companies and laboratories, and geologic outcrops of producing formations. There are many opportunities for summer and part-time employment in the oil and gas industry.

Each summer, several graduate students assist with the field sessions designed for undergraduate students. The field sessions in the past several years have included visits to oil and gas operations in Alaska, Canada, Southern California, the Gulf Coast, the northeast U.S., the Rocky Mountain regions, and western Colorado.

The Petroleum Engineering Department encourages student involvement with the Society of Petroleum Engineers, the American Association of Drilling Engineers and the American Rock Mechanics Association. The department provides some financial support for students attending the annual technical conferences for these professional societies.

## Program Requirements

**Master of Engineering**

Candidates for the non-thesis **Master of Engineering** degree must complete a minimum of 30 hours of graduate course credit. At least 15 of the credits must be from the Petroleum Engineering Department. Up to 12 graduate credits can be transferred from another institution. All courses must be approved by the student's advisor and the department head. No graduate committee is required. No more than 6 credits can be earned through independent study.

## Master of Science

Candidates for the **Master of Science** degree must complete at least 24 graduate credits of course work, approved by the candidate's graduate committee, and a minimum of 6 hours of research credit. At least 12 of the course credits must be from the Petroleum Engineering Department. Up to 9 credits may be transferred from another institution. For the MS degree, the student must demonstrate ability to observe, analyze, and report original scientific research. For other requirements, refer to the general instructions of the Graduate School (p. 4) in this bulletin.

## Doctor of Philosophy

A candidate for the **PhD** must complete at least 48 hours of course credit and a minimum of 30 credits of research beyond the bachelor's degree. A student with a master's degree is allowed to transfer up to 24 hours of course credit from the Master's degree into the PhD program upon approval of the department and the student's thesis committee. Students may additionally transfer up to 21 graduate credits of course work from another institution with the approval of the graduate advisor, under the condition that these hours were not previously used for a degree or a certificate. PhD students must complete at least half of their minimally required course credits from the Petroleum Engineering Department and a minimum of 6 credits of their required course credit outside the Petroleum Engineering Department. The student's faculty advisor, thesis committee, and the department head must approve the course selection. Full-time PhD students must satisfy the following requirements for admission to candidacy within the first two calendar years after enrolling in the program:

1. Have a thesis committee appointment form on file,
2. Complete all prerequisite courses successfully,
3. Demonstrate adequate preparation for and satisfactory ability to conduct doctoral research by successfully completing a series of written and/or oral examinations and fulfilling the other requirements of their graduate committees as outlined in the department's graduate handbook.

Failure to fulfill these requirements within the time limits specified above may result in immediate mandatory dismissal from the PhD program according to the procedure outlined in the section of this Bulletin titled General Regulations—Unsatisfactory Academic Performance—Unsatisfactory Academic Progress Resulting in Probation or Discretionary Dismissal. For other requirements, refer to the general directions of the Graduate School (p. 4) in this bulletin and/or the department's Graduate Student Handbook.

## Combined Undergraduate/Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

## Courses

**PEGN501. APPLICATIONS OF NUMERICAL METHODS TO PETROLEUM ENGINEERING. 3.0 Semester Hrs.**
The course will solve problems of interest in Petroleum Engineering through the use of spreadsheets on personal computers and structured FORTRAN programming on PCs or mainframes. Numerical techniques will include methods for numerical quadrature, differentiation, interpolation, solution of linear and nonlinear ordinary differential equations, curve fitting and direct or iterative methods for solving simultaneous equations. Prerequisites: PEGN414 and PEGN424. 3 hours lecture; 3 semester hours.

**PEGN502. ADVANCED DRILLING FLUIDS. 3.0 Semester Hrs.**
The physical properties and purpose of drilling fluids are investigated. Emphasis is placed on drilling fluid design, clay chemistry, testing, and solids control. Prerequisite: PEGN311. 2 hours lecture, 3 hours lab; 3 semester hours.

**PEGN503. INTEGRATED EXPLORATION AND DEVELOPMENT. 3.0 Semester Hrs.**
(I) Students work alone and in teams to study reservoirs from fluvial-deltaic and valley fill depositional environments. This is a multidisciplinary course that shows students how to characterize and model subsurface reservoir performance by integrating data, methods and concepts from geology, geophysics and petroleum engineering. Activities include field trips, computer modeling, written exercises and oral team presentations. Prerequisite: none. 2 hours lecture, 3 hours lab; 3 semester hours. Offered fall semester, odd years.

**PEGN504. INTEGRATED EXPLORATION AND DEVELOPMENT. 3.0 Semester Hrs.**
(I) Students work in multidisciplinary teams to study practical problems and case studies in integrated subsurface exploration and development.

The course addresses emerging technologies and timely topics with a general focus on carbonate reservoirs. Activities include field trips, 3D computer modeling, written exercises and oral team presentation. Prerequisite: none. 3 hours lecture and seminar; 3 semester hours. Offered fall semester, even years.

**PEGN505. HORIZONTAL WELLS: RESERVOIR AND PRODUCTION ASPECTS. 3.0 Semester Hrs.**
This course covers the fundamental concepts of horizontal well reservoir and production engineering with special emphasis on the new developments. Each topic covered highlights the concepts that are generic to horizontal wells and draws attention to the pitfalls of applying conventional concepts to horizontal wells without critical evaluation. There is no set prerequisite for the course but basic knowledge on general reservoir engineering concepts is useful. 3 hours lecture; 3 semester hours.

**PEGN506. ENHANCED OIL RECOVERY METHODS. 3.0 Semester Hrs.**
Enhanced oil recovery (EOR) methods are reviewed from both the qualitative and quantitative standpoint. Recovery mechanisms and design procedures for the various EOR processes are discussed. In addition to lectures, problems on actual field design procedures will be covered. Field case histories will be reviewed. Prerequisite: PEGN424. 3 hours lecture; 3 semester hours.

**PEGN508. ADVANCED ROCK PROPERTIES. 3.0 Semester Hrs.**
Application of rock mechanics and rock properties to reservoir engineering, well logging, well completion and well stimulation. Topics covered include: capillary pressure, relative permeability, velocity effects on Darcy's Law, elastic/mechanical rock properties, subsidence, reservoir compaction, and sand control. Prerequisites: PEGN423 and PEGN426. 3 hours lecture; 3 semester hours.

**PEGN511. ADVANCED THERMODYNAMICS AND PETROLEUM FLUIDS PHASE BEHAVIOR. 3.0 Semester Hrs.**
Essentials of thermodynamics for understanding the phase behavior of petroleum fluids such as natural gas and oil. Modeling of phase behavior of single and multi-component systems with equations of states with a brief introduction to PVT laboratory studies, commercial PVT software, asphaltenes, gas hydrates, mineral deposition, and statistical thermodynamics. 3 hours lecture; 3 semester hours. Prerequisites: PEGN312, PEGN305.
**Course Learning Outcomes**

- Identify the fundamental properties of reservoir rocks and their impact on reservoir behavior, including porosity, saturations, and formation compressibility, for comprehensive understanding in petroleum engineering applications.

**PEGN512. ADVANCED GAS ENGINEERING. 3.0 Semester Hrs.**
The physical properties and phase behavior of gas and gas condensates will be discussed. Flow through tubing and pipelines as well as through porous media is covered. Reserve calculations for normally pressured, abnormally pressured and water drive reservoirs are presented. Both stabilized and isochronal deliverability testing of gas wells will be illustrated. Prerequisite: PEGN423. 3 hours lecture; 3 semester hours.

**PEGN513. RESERVOIR SIMULATION I. 3.0 Semester Hrs.**
The course provides the rudiments of reservoir simulation, which include flow equations, solution methods, and data requirement. Specifically, the course covers: equations of conservation of mass, conservation of momentum, and energy balance; numerical solution of flow in petroleum reservoirs by finite difference (FD) and control volume FD; permeability tensor and directional permeability; non-Darcy flow; convective flow and numerical dispersion; grid orientation problems; introduction to finite element and mixed finite-element methods; introduction to hybrid analytical/numerical solutions; introduction to multi-phase flow models; relative permeability, capillary pressure and wettability issues; linear equation solvers; streamline simulation; and multi-scale simulation concept. Prerequisite: PEGN424 or equivalent, strong reservoir engineering background, and basic computer programming knowledge. 3 credit hours. 3 hours of lecture per week.

**PEGN515. ADVANCED RESERVOIR ENGINEERING. 3.0 Semester Hrs.**
Reservoir Engineering overview. Predicting hydrocarbon in place; volumetric method, deterministic and probabilistic approaches, material balance, water influx, graphical techniques. Fluid flow in porous media; continuity and diffusivity equations. Well performance; productivity index for vertical, perforated, fractured, restricted, slanted, and horizontal wells, inflow performance relationship under multiphase flow conditions. Combining material balance and well performance equations. Future reservoir performance prediction; Muskat, Tarner, Carter and Tracy methods. Fetkovich decline curves. Reservoir simulation; fundamentals and formulation, streamline simulation, integrated reservoir studies. 3 hours lecture, 3 semester hours.

**PEGN517. ADVANCED DRILLING ENGINEERING. 3.0 Semester Hrs.**
Drilling Engineering overview. Subjects to be covered include overall drilling organization, contracting, and reporting; basic drilling engineering principles and equipment; drilling fluids, hydraulics, and cuttings transport; drillstring design; drill bits; drilling optimization; fishing operations; well control; pore pressure and fracture gradients, casing points and design; cementing; directional drilling and horizontal drilling. 3 hours lecture, 3 semester hours.

**PEGN518. ADVANCED PRODUCTION ENGINEERING. 3.0 Semester Hrs.**
This course provides the fundamental concepts in the production area, including Inflow Performance Relationships (IPR), Outflow Performance Relationship (OPR) (or Multiphase Flow in Wells), and Nodal Analysis. It also teaches the current most widely used artificial lift methods, including Gas Lift, ESP, and Sucker Rod Pump systems, and their design and application/challenges for conventional and unconventional reservoirs. Also covered are the introduction of major flow assurance issues, such as liquid loading, terrain and severe slugging, wax, gas hydrate, and emulsion, and their prevention and mitigation, as well as the surface facilities for gas and oil processing. Students will have the opportunities to write multiphase flow simulators, which are essential in production design and flow assurance problems prediction and management. Some widely used commercial production design software (PIPESIM and OLGA) will also be taught and the students will use them in the production system design.
**Course Learning Outcomes**

**PEGN519. ADVANCED FORMATION EVALUATION. 3.0 Semester Hrs.**
A detailed review of wireline well logging and evaluation methods stressing the capability of the measurements to determine normal and special reservoir rock parameters related to reservoir and production problems. Computers for log processing of single and multiple wells. Utilization of well logs and geology in evaluating well performance before, during, and after production of hydrocarbons. The sensitivity of formation evaluation parameters in the volumetric determination of petroleum in reservoirs. Prerequisite: PEGN419. 3 hours lecture; 3 semester hours.

**PEGN522. ADVANCED WELL STIMULATION. 3.0 Semester Hrs.**
(I) Basic applications of rock mechanics to petroleum engineering problems. Hydraulic fracturing; acid fracturing, fracturing simulators; fracturing diagnostics; sandstone acidizing; sand control, and well bore stability. Different theories of formation failure, measurement of mechanical properties. Review of recent advances and research areas. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

**PEGN524. PETROLEUM ECONOMICS AND MANAGEMENT. 3.0 Semester Hrs.**
Business applications in the petroleum industry are the central focus. Topics covered are: fundamentals of accounting, oil and gas accounting, strategic planning, oil and gas taxation, oil field deals, negotiations, and the formation of secondary units. The concepts are covered by forming companies that prepare proforma financial statements, make deals, drill for oil and gas, keep accounting records, and negotiate the participation formula for a secondary unit. Prerequisite:
PEGN422. 3 hours lecture; 3 semester hours.

**PEGN530. ENVIRONMENTAL LAW AND SUSTAINABILITY. 3.0 Semester Hrs.**
Equivalent with CEEN492,CEEN592,
(II) In this course students will be introduced to the fundamental legal principles that are relevant to sustainable engineering project development. General principles of United States(U.S.) environmental regulation pertaining to air quality, water quality, waste management, hazardous substances remediation, regulation of chemical manufacture and distribution, natural resources, and energy will be discussed parallel with international laws pertaining to environmental protection and human rights. In the context of engineering project design, students will explore legal, societal, and ethical risks, and risk mitigation methodologies. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

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**PEGN540. PETROLEUM DATA ANALYSIS. 3.0 Semester Hrs.**
This course will take a detailed look at the opportunities, challenges and specific requirements for petroleum data analytics for the energy industry. It starts with an introduction to data analysis and visualization packages. Three projects are assigned in drilling, production, and reservoir data analysis along with data visualization techniques. The student will be required to prepare both oral and written project updates and final results. Prerequisite: PEGN438 or instructor consent.
**Course Learning Outcomes**

- Contribute toward the significant technical challenges created by large data environments, including architecture, security, integrity, management, scalability, artificial intelligence topics, and distribution.
- Apply the principles and application of informatics, and the goals of enterprise intelligence as applied to the energy industry.
- Prepare and analyze data from various petroleum data streams including drilling, completions, stimulation, production, and reservoir management.
- Interpret petroleum data and derive useful conclusions.
- Demonstrate professionalism through attendance, demeanor, participation, exhibiting integrity, accepting responsibility, taking initiative, team participation and providing leadership as necessary to ensure project success.
- Create formal and informal communications for individual, team, and industry/company use that document and facilitate progress and enhance the impact of the final design.

**PEGN547. PHYSICS, MECHANICS AND PETROPHYSICS OF ROCKS. 3.0 Semester Hrs.**
(I) This course will discuss topics in rock physics, rock mechanics and petrphysics as outlined below. The class is a combination of lectures, laboratory sessions, and critical reading and discussion of papers. Topics: Stresses, strains, stiffnesses, rock physics, petrophysics: wettability: shale analysis: seismic & log expression of various formations: diagenesis: formation evaluation. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- First-order Level Learning Objectives • Gain an introduction to and a working knowledge of the main topics in rock physics • Understand and evaluate technical topics related to rock physics applications • Have insight into basic techniques to evaluate reservoirs • Learn tools to assess reserves, and learn best techniques to use rock physics principles
- Second-order Learning Objectives • identify major & minor rock-forming minerals • evaluate or recall elastic properties of major rock-forming minerals • classify mineral constitutents as load-bearing or pore-filling • compute modulus of a dry rock frame constructed with major minerals • know isotropic and other (Major) symmetries • predict modulus changes in fluid and frame with stress • predict modulus changes with cementation • evaluate / defend role of porosity, cementation and diagenesis on elastic properties • evaluate and appraise elastic modulus of frame with geological and well log information • explain differences between static and dynamic stresses, strains and moduli • classify lithological texture to expected acoustic anisotropy • compute elastic bounds: Voigt, Reuss, Hashin-Shtrikman, modified H-S • compute Empirical velocity models

**PEGN551. PETROLEUM DATA ANALYTICS - FUNDAMENTALS. 3.0 Semester Hrs.**
Introduction to advanced data analytics in the Digital Oilfield. Comprehensive overview of the fundamental building blocks of the digital oilfield from the convergence of operational technology (field instrumentation and control systems) with corporate information technology infrastructure. An understanding of the data foundation for a typical oil and gas exploration and production company and the challenges of Big Data to oilfield operations (volumes, variety, velocity, and data quality). Prerequisite: DSCI403, DSCI530 or MATH530 or Instructor Approval.
**Course Learning Outcomes**

- A review of the objectives and results from the digital oilfield since 2000 and a discussion of what is new today (lower for much longer oil prices and emerging digital technologies)
- Convergence of OT (operational technology) and IT (information technology) systems. From sensors and control systems (SCADA), to remote decision support environments, to workflow automation, to process optimization
- Review of often used analytical techniques (regression analysis, neural networks, machine learning, deep learning). Machine Learning overview with Python programming and Jypter Notebook platform
- Review of Business Intelligence (reporting), Data Visualization (dashboards, data story telling) and Artificial Intelligence approaches, the strengths, and weaknesses of each.

**PEGN552. PETROLEUM DATA ANALYTICS - APPLICATIONS. 3.0 Semester Hrs.**
A continuation of the advanced data analytics in the Digital Oilfield. This capstone course will be to apply learnings from the previous sequence of courses to drilling/completions improvement, production analysis, reservoir management optimization, and unconventional resource development. The course requires the ability of the student to be able to collect, manage, manipulate, analyze, develop insights, and report using both written and oral means those insights using good data visualizations. Prerequisite: PEGN551 or Instructor Consent.
**Course Learning Outcomes**

- The application of data computational techniques for developing and measuring key performance indications for oil and gas, geothermal, and other drilling and/or completion operations
- • The application of predictive analytics for optimization of oil and gas production processes.
- • The application of data analysis techniques for determining best practice for the management of sub-surface resource development.
- • The application of data analysis techniques for predicting and optimizing the development and production of unconventional resources – shale development, tight gas sands, enhanced oil recovery, and other esoteric resource development.

**PEGN577. WORKOVER DESIGN AND PRACTICE. 3.0 Semester Hrs.**
Workover Engineering overview. Subjects to be covered include Workover Economics, Completion Types, Workover Design Considerations, Wellbore Cleanout (Fishing), Workover Well Control, Tubing and Workstring Design, SlicklineOperations, Coiled Tubing Operations, Packer Selection, Remedial Cementing Design and Execution, Completion Fluids, Gravel Packing, and Acidizing. 3 hours lecture, 3 semester hours.

**PEGN590. RESERVOIR GEOMECHANICS. 3.0 Semester Hrs.**
The course provides an introduction to fundamental rock mechanics concepts and aims to emphasize their role in exploration, drilling, completion and production engineering operations. Basic stress and strain concepts, pore pressure, fracture gradient and in situ stress magnitude and orientation determination and how these properties are obtained from the field measurements, mechanisms of deformation in rock, integrated wellbore stability analysis, depletion induced compaction and associated changes in rock properties and formation strength, hydraulic fracturing and fracture stability are among the topics to be covered in this rock course. Naturally fractured formation properties and how they impact the characteristics measured in the laboratory and in field are also included in the curriculum. Several industry speakers are invited as part of the lecture series to bring practical aspects of the fundamentals of geomechanics covered in the classroom. In addition, Petrel, FLAC3D and FRACMAN software practices with associated assignments are offered to integrate field data on problems including in situ stress magnitude and orientations, pore pressure and fracture gradient prediction and rock property determination using laboratory core measurements, logs, seismic, geological data. Problems are assign for students to use the field and laboratory data to obtain static and dynamic moduli, rock failure criteria, wellbore stress concentration and failure, production induced compaction/subsidence and hydraulic fracture mechanics.

**PEGN591. SHALE RESERVOIR ENGINEERING. 3.0 Semester Hrs.**
Equivalent with PEGN615,
Fundamentals of shale-reservoir engineering and special topics of production from shale reservoirs are covered. The question of what makes shale a producing reservoir is explored. An unconventional understanding of shale-reservoir characterization is emphasized and the pitfalls of conventional measurements and interpretations are discussed. Geological, geomechanical, and engineering aspects of shale reservoirs are explained. Well completions with emphasis on hydraulic fracturing and fractured horizontal wells are discussed from the viewpoint of reservoir engineering. Darcy flow, diffusive flow, and desorption in shale matrix are covered. Contributions of hydraulic and natural fractures are discussed and the stimulated reservoir volume concept is introduced. Interactions of flow between fractures and matrix are explained within the context of dual-porosity modeling. Applications of pressure-transient, rate-transient, decline-curve and transient-productivity analyses are covered. Field examples are studied. 3 hours lecture; 3 semester hours.

**PEGN592. GEOMECHANICS FOR UNCONVENTIONAL RESOURCES. 3.0 Semester Hrs.**
A wide spectrum of topics related to the challenges and solutions for the exploration, drilling, completion, production and hydraulic fracturing of unconventional resources including gas and oil shale, heavy oil sand and carbonate reservoirs, their seal formations is explored. The students acquire skills in integrating and visualizing multidiscipline data in Petrel (a short tutorial is offered) as well as assignments regarding case studies using field and core datasets. The role of integrating geomechanics data in execution of the exploration, drilling, completion, production, hydraulic fracturing and monitoring of pilots as well as commercial applications in unlocking the unconventional resources are pointed out using examples. Prerequisite: PEGN590. 3 hours lecture; 3 semester hours.

**PEGN593. ADVANCED WELL INTEGRITY. 3.0 Semester Hrs.**
Fundamentals of wellbore stability, sand production, how to keep wellbore intact is
covered in this course. The stress alterations in near wellbore region and associated consequences in the form of well failures will be covered in detailed theoretically and with examples from deepwater conventional wells and onshore unconventionalwell operations. Assignments will be given to expose the students to the real field data to interpret and evaluate cases to determinepractical solutions to drilling and production related challenges. Fluid pressure and composition sensitivity of various formations will be studied. 3 hours lecture; 3 semester hours.

**PEGN594. ADVANCED DIRECTIONAL DRILLING. 3.0 Semester Hrs.**
Application of directional control and planning to drilling. Major topics covered include: Review of procedures for the drilling of directional wells. Section and horizontal view preparation. Two and three dimensional directional planning. Collision diagrams. Surveying and trajectory calculations. Surface and down hole equipment. Common rig operating procedures, and horizontal drilling techniques. Prerequisite: PEGN311 or equivalent. 3 hours lecture; 3 semester hours.

**PEGN596. ADVANCED WELL CONTROL. 3.0 Semester Hrs.**
Principles and procedures of pressure control are taught with the aid of a full-scale drilling simulator. Specifications and design of blowout control equipment for onshore and offshore drilling operations, gaining control of kicks, abnormal pressure detection, well planning for wells containing abnormal pressures, and kick circulation removal methods are taught. Students receive hands-on training with the simulator and its peripheral equipment. Prerequisite: PEGN311. 3 hours lecture; 3 semester hours.

**PEGN597. TUBULAR DESIGN. 3.0 Semester Hrs.**
Fundamentals of tubulars (casing, tubing, and drill pipe) design applied to drilling. Major topics covered include: Dogleg running loads. Directional hole considerations. Design criteria development. Effects of formation pressures. Stability loads after cementing. Effects of temperature, pressure, mud weights, and cement. Helical bending of tubing. Fishing loads. Micro-annulus problem. Strengths of API tubulars. Abrasive wear while rotating drill pipe. How to design for hydrogen sulfide and fatigue

corrosion. Connection selection. Common rig operating procedures. Prerequisites: PEGN311 and PEGN361 or equivalent. 3 hours lecture; 3 semester hours.

**PEGN598. SPECIAL TOPICS IN PETROLEUM ENGINEERING. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**PEGN598. SPECIAL TOPICS. 0-6 Semester Hr.**

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**PEGN598LA. SPECIAL TOPICS LAB. 0-6 Semester Hr.**

**PEGN598. SPECIAL TOPICS. 0-6 Semester Hr.**

**PEGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**PEGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

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**PEGN601. APPLIED MATHEMATICS OF FLUID FLOW IN POROUS MEDIA. 3.0 Semester Hrs.**
This course is intended to expose petroleum-engineering students to the special mathematical techniques used to solve transient flow problems in porous media. Bessel’s equation and functions, Laplace and Fourier transformations, the method of sources and sinks, Green’s functions, and boundary integral techniques are covered. Numerical evaluation of various reservoir engineering solutions, numerical Laplace transformation and inverse transformation are also discussed. 3 hours lecture; 3 semester hours.

**PEGN604. INTEGRATED FLOW MODELING. 3.0 Semester Hrs.**
Students will study the formulation, development and application of a reservoir flow simulator that includes traditional fluid flow equations and a petrophysical model. The course will discuss properties of porous media within the context of reservoir modeling, and present the mathematics needed to understand and apply the simulator. Simulator applications will be interspersed throughout the course. 3 hours lecture; 3 semester hours.

**PEGN605. ADVANCED WELL TESTING ANALYSIS. 3.0 Semester Hrs.**
Various well testing procedures and interpretation techniques for individual wells or groups of wells. Application of these techniques to field development, analysis of well problems, secondary recovery, and reservoir studies. Productivity, gas well testing, pressure buildup and drawdown, well interference, fractured wells, type curve matching, and shortterm testing. Prerequisite: PEGN426. 3 hours lecture; 3 semester hours.

**PEGN608. MULTIPHASE FLUID FLOW IN POROUS MEDIA. 3.0 Semester Hrs.**
The factors involved in multiphase fluid flow in porous and fractured media. Physical processes and mathematical models for micro- and macroscopic movement of multiphase fluids in reservoirs. Performance evaluation of various displacement processes in the laboratory as well as in the petroleum field during the secondary and EOR/IOR operations. Prerequisite: PEGN 424, 3 hours lecture; 3 semester hours.

**PEGN614. RESERVOIR SIMULATION II. 3.0 Semester Hrs.**
The course reviews the rudiments of reservoir simulation and flow equations, solution methods, and data requirement. The course emphasizes multi-phase flow and solution techniques; teaches the difference between conventional reservoir simulation, compositional modeling and multi-porosity modeling; teaches how to construct three-phase relative permeability from water-oil and gas-oil relative permeability data set; the importance of capillary pressure measurements and wetability issues; discusses the significance of gas diffusion and interphase mass transfer. Finally, the course develops solution techniques to include time tested implicit-pressure-explicitsaturation, sequential and fully implicit methods. Prerequisite: PEGN513 or equivalent, strong reservoir engineering background, and basic computer programming knowledge. 3 credit hours. 3 hours of lecture per week.

**PEGN620. NATURALLY FRACTURED RESERVOIRS -- ENGINEERING AND RESERVOIR SIMULATION. 3.0 Semester Hrs.**
The subsurface crust of the Earth is highly fractured which impacts mass and energy transport associated with aquifers, petroleum reservoirs, hydrothermal reservoirs, hot-dry-rock enhanced geothermal systems (EGS), and waste disposal in igneous and metamorphic rocks. The course covers reservoir engineering, well testing, and simulation aspects of naturally fractured reservoirs. Specifics include: fractures in subsurface rocks, connectivity and network; fracture flow properties; physical principles underlying reservoir engineering and modeling naturally fractured reservoirs; local and global effects of viscous, capillary, gravity and molecular diffusion flows; dual-porosity/dual-permeability models; multi-scale fracture models; transient testing with non-Darcy flow effects; tracer injection and breakthrough analysis; geomechanics of fractures; compositional model; coal-bed gas model; oil and gas from fractured shale; improved and enhanced oil recovery in naturally fracture reservoirs. Prerequisites: PEGN513 or equivalent, strong reservoir engineering background, and basic computer programming knowledge.
**Course Learning Outcomes**

- Analyze the significance of mass and energy transport models in subsurface energy resources engineering to inform reservoir performance assessments.

- Apply advance engineering strategies to address complex reservoir system challenges, utilizing critical thinking to conduct and communicate research effectively.
- Develop and implement numerical algorithms for solving fluid flow and heat transport equations in fractured rock environments, demonstrating proficiency with data analysis tools.
- Synthesize computational methods to create solutions for non-linear, real-world mass and heat transport problems, enhancing AI-driven models.
- Design practical solutions to real-world engineering problems by integrating coursework, software, and communication skills.

**PEGN624. COMPOSITIONAL MODELING - APPLICATION TO ENHANCED OIL RECOVERY. 3.0 Semester Hrs.**
Efficient production of rich and volatile oils as well as enhanced oil recovery by gas injection (lean and rich natural gas, CO2, N2, air, and steam) is of great interest in the light of greater demand for hydrocarbons and the need for CO2 sequestration. This course is intended to provide technical support for engineers dealing with such issues. The course begins with a review of the primary and secondary recovery methods, and will analyze the latest worldwide enhanced oil recovery production statistics. This will be followed by presenting a simple and practical solvent flooding model to introduce the student to data preparation and code writing. Next, fundamentals of phase behavior, ternary phase diagram, and the Peng-Robinson equation of state will be presented. Finally, a detailed set of flow and thermodynamic equations for a full-fledged compositional model, using molar balance, equation of motion and the afore-mentioned equation of state, will be developed and solution strategy will be presented. Prerequisite: PEGN513 or equivalent, strong reservoir engineering background, and basic computer programming knowledge. 3 hours lecture; 3 semester hours.

**PEGN660. CARBONATE RESERVOIRS - EXPLORATION TO PRODUCTION. 3.0 Semester Hrs.**
Equivalent with GEOL660,
(II) This course will include keynote lectures and seminars on the reservoir characterization of carbonate rocks, including geologic description, petrophysics and production engineering. Course will focus on the integration of geology, rock physics, and engineering to improve reservoir performance. Application of reservoir concepts in hands-on exercises, that include a reflection seismic, well log, and core data. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- 1) working knowledge of carbonate sedimentology and diagenesis its use in construction reservoir geometry and pore system architecture to design effective production strategies; 2) working knowledge of production engineering in carbonate reservoirs with a focus on dual porosity media (matrix and fractures), multi-scale physics and geo-mechanics in fractured carbonate reservoirs to help design reservoir stimulation models; and 3) working knowledge of how to integrate geology, geophysics, petrophysics, and engineering to increase reservoir performance.

**PEGN681. PETROLEUM ENGINEERING SEMINAR. 1.0 Semester Hr.**
Comprehensive reviews of current petroleum engineering literature, ethics, and selected topics as related to research and professionalism. 0 credit hours, except in students' final semester, in which it will be one credit.

**PEGN698. SPECIAL TOPICS IN PETROLEUM ENGINEERING. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**PEGN698. SPECIAL TOPICS. 0-6 Semester Hr.**

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**PEGN698. SPECIAL TOPICS. 0-6 Semester Hr.**

**PEGN699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**PEGN699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**PEGN699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**PEGN707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.**
(I, II, S) Research credit hours required for completion of a Masters-level thesis or Doctoral dissertation. Research must be carried out under the direct supervision of the student's faculty advisor. Variable class and semester hours. Repeatable for credit.

**SYGN683. ORAL COMMUNICATION SKILLS. 1.0 Semester Hr.**
This course is designed for ME, MS and PhD students and focuses on designing and delivering technical presentations. Course assignments will be based on technical and non-technical material relating to earth, energy, and the environment and will include the topics of professionalism, ethics and diversity. Students will work individually and in multicultural teams on assignments. There are no prerequisites for this course, however, proficiency with the English language, both oral and written, is expected prior to enrollment.
**Course Learning Outcomes**

- Identify ethical considerations in technical communication.
- Identify audience considerations in technical communication.
- Prepare and deliver technical presentations.

**SYGN684. WRITING SKILLS. 2.0 Semester Hrs.**
This course is designed for MS and PhD students and will focus on the research process and the technical writing process. Course assignments will be based on technical and non-technical material relating to earth, energy, and the environment and will include the topics of professionalism, ethics and diversity. Students will work individually and in multicultural teams on assignments. There are no prerequisites for PEGN684, however, proficiency with the English language, both oral and written, is expected prior to enrollment.
**Course Learning Outcomes**

- Analyze and critique peer-reviewed journal articles
- Organize information and write technical documents including memos, abstracts, proposals, thesis/dissertations, and formal analytical reports.

- Discuss workplace and societal issues including professionalism, ethics, and diversity.

## Professors

Hossein Kazemi, Chesebro' Distinguished Chair

Jennifer L. Miskimins, Department Head, F.H. "Mick" Merelli/Cimarex Energy Distinguished Department Head

Erdal Ozkan

Yu-Shu Wu

## Associate Professors

Pejman Tahmasebi

Luis E. Zerpa, Associate Department Head, Harry D. Campbell Chair in Petroleum Engineering

## Assistant Professors

Parisa Bazazi

Yilan Fan

Serveh Kamrava

Mohamed Khaled

## Teaching Professor

Linda A. Battalora

## Teaching Associate Professors

Mansur Ermila

Mark G. Miller

## Research Professor

Ali Tura

## Research Associate Professor

Philip H. Winterfeld

## Professor Emeritus

Ramona M. Graves, Professor and Dean Emeritus

Bill Scoggins, President Emeritus

Craig W. Van Kirk, Professor Emeritus

## Associate Professor Emeritus

Alfred W. Eustes III, Associate Professor Emeritus

Richard Christiansen, Associate Professor Emeritus

# Physics

## Degrees Offered

- Master of Science (Applied Physics)
- Master of Science Non-Thesis (Applied Physics)
- Doctor of Philosophy (Physics)
- Graduate Certificate (Optics for Engineering)

Program Description

The Physics Department at Mines offers a full program of instruction and research leading to the MS in Applied Physics or PhD in Physics. It also contributes to graduate interdisciplinary programs in Materials Science (MS and PhD), Nuclear Engineering (MS and PhD), and Quantum Engineering (MS). The research in these graduate programs is supported by external grants and contracts totaling $6.37M/year in research expenditures. Research in the department is organized under three primary themes: subatomic physics, condensed matter physics, and applied optics. With 23 faculty, 66 graduate students, and 225 undergraduate physics majors, the Physics Department at Mines is a vibrant intellectual community providing high-quality education in state-of-the-art facilities.

Graduate students are given a solid background in the fundamentals of classical and modern physics at an advanced level and are encouraged early in their studies to learn about the research interests of the faculty so that a thesis topic can be identified.

## Program Requirements

Students entering graduate programs in the Physics Department will select an initial program in consultation with the departmental graduate student advising committee until such time as a research field has been chosen and a thesis committee appointed.

## Master of Science

*Requirements*:

**MS-Thesis in Applied Physics**: 18 credits of course work in an approved program, 2 credits of seminar, plus 10 credits of research credit, with a satisfactory thesis.

**MS-non-Thesis in Applied Physics**: 28 credits of course work and 2 credits of seminar. At least 21 of the required 30 credits of course work must be taken as a registered master's degree student at Mines. The program will allow up to 7 credits of independent study coursework to count towards the non-thesis MS degree. Up to 9 credits of graduate courses may be transferred into the degree program, provided that those courses have not been used as credit toward a Bachelor's degree. The student's committee makes decisions on courses to be taken, transfer credit, and examines the student's written report and oral presentation resulting from an independent study.

## Mines' Combined Undergraduate/Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

## Doctor of Philosophy

Requirements: 32 credits of coursework in an approved program plus 40 credits of research credit, with a satisfactory thesis. 12 credits of course work will be in a specialty topic area defined in consultation with the thesis advisor. Possible specialty topic areas within the Physics Department exist in Optical Science and Engineering, Condensed Matter Physics, Theoretical Physics, Renewable Energy Physics, and Nuclear/ Particle Physics and Astrophysics.

To demonstrate adequate preparation for the PhD degree in Physics, each student must achieve a grade point average of 3.0 or better in the core courses. Students not meeting this standard must pass oral examinations covering the relevant course content or retake the courses within one year. This process is part of the requirement for admission to candidacy, which full time PhD students must complete within two calendar years of admission, as described in the campus-wide graduate degree requirements (p. 29) section of this bulletin. Other degree requirements, time limits, and procedural details can be found in the Physics Department Graduate Student Advising Brochure.

## Physics Colloquium

All full-time physics graduate students must attend the Physics Colloquium, which is represented in the curriculum by the Graduate Seminar courses. Students must take one of these courses every semester that they are enrolled at Mines. Those students who are in the MS Program, sign up for PHGN501 (fall) and PHGN502 (spring). Students in the PhD program sign up for PHGN601 (fall) and PHGN602 (spring). At the end of each semester students are assigned either a satisfactory or unsatisfactory progress grade, based on attendance, until the final semester of the student's degree program, when a letter grade is assigned based on all prior semesters' attendance grades. As a result, while these courses are taken each year, only 1 hour total of course credit is conferred for each of 501, 502, 601, or 602. Students who have official part-time status and who have already taken at least one semester of 501 and 502 for the MS degree, or 601 and 602 for the PhD degree are not required to sign up for Graduate Seminar during subsequent semesters.

## Prerequisites

The Graduate School of Colorado School of Mines is open to graduates from four-year programs at accredited colleges or universities. Admission to the Physics Department MS and PhD programs is competitive and is based on an evaluation of undergraduate performance, standardized test scores, and references. The undergraduate course of study of each applicant is evaluated according to the requirements of the Physics Department.

## Required Curriculum

## Master of Science (with Thesis) in Applied Physics

| Core Courses | | |
|---|---|---|
| PHGN511 | MATHEMATICAL PHYSICS | 3.0 |
| PHGN515 | GRADUATE LABORATORY | 3.0 |
| PHGN520 | QUANTUM MECHANICS I | 3.0 |
| PH ELECT | Electives ** | 9.0 |
| PHGN501 & PHGN502 | GRADUATE SEMINAR and GRADUATE SEMINAR * | 2.0 |
| PHGN707 | GRADUATE THESIS / DISSERTATION RESEARCH CREDIT | 10.0 |
| **Total Semester Hrs** | | **30.0** |

* Graduate Seminar: Each full-time MS graduate student will register for Graduate Seminar each semester for a total of 2 cumulative credits over the degree.

** Electives maybe chosen from classes taught in physics or relevant classes taught in other departments, as approved by the graduate advisor and thesis committee.

## Master of Science (non-Thesis) in Applied Physics

| Core Courses | | |
|---|---|---|
| PHGN511 | MATHEMATICAL PHYSICS | 3.0 |
| PHGN515 | GRADUATE LABORATORY | 3.0 |
| PH ELECT | Electives ** | 22.0 |
| PHGN501 & PHGN502 | GRADUATE SEMINAR and GRADUATE SEMINAR * | 2.0 |
| **Total Semester Hrs** | | **30.0** |

* Graduate Seminar: Each full-time MS graduate student will register for Graduate Seminar each semester for a total of 2 cumulative credits over the degree.

** Electives may be chosen from additional classes in physics, other disciplines relevant to their focus, and one of CSM 501 (Grad Student Skills), SYGN 501 (research skills for graduate students), or responsible conduct of research (PHGN 503 or SYGN 502).
At least one elective must be in a course with a significant laboratory or design emphasis. Courses with a laboratory component include, PHGN 532 Low Temp Microwave measurement, PHGN 535 Microprocessing lab, and PHGN 581 laser physics. Coursework with heavily applied components include, MLGN502 Solid State Physics, PHGN 504 Radiation Detection, PHGN 519 Fundamentals of Quantum Information, PHGN 542 Solid State Devices, PHGN 566 Modern optical Engineering. Other classes that fulfil this requirement may be approved by the graduate advisor.
The program will allow up to 7 credits of independent study coursework to count towards the non-thesis MS degree.

## Doctor of Philosophy in Physics

| Core Courses | | |
|---|---|---|
| PHGN507 | ELECTROMAGNETIC THEORY I | 3.0 |
| PHGN511 | MATHEMATICAL PHYSICS | 3.0 |
| PHGN515 | GRADUATE LABORATORY | 3.0 |
| PHGN520 | QUANTUM MECHANICS I | 3.0 |
| PHGN521 | QUANTUM MECHANICS II | 3.0 |
| PHGN530 | STATISTICAL MECHANICS | 3.0 |
| PHGN601 & PHGN602 | ADVANCED GRADUATE SEMINAR and ADVANCED GRADUATE SEMINAR * | 2.0 |
| PH ELECT | Special topic area electives | 12.0 |
| PHGN707 | GRADUATE THESIS / DISSERTATION RESEARCH CREDIT | 40.0 |
| **Total Semester Hrs** | | **72.0** |

* Graduate Seminar: Each full-time PhD graduate student will register for Graduate Seminar each semester for a total of 2 cumulative credits over the degree.

## Fields of Research

**Applied Optics and Biophysics:** lasers, ultrafast optics, non-linear optics, laser-produced plasmas, micromachining, multiphoton microscopy, single-molecule microscopy, total internal reflection microscopy, biophysical mechanisms of collagen fibril degradation, novel imaging techniques.

**Subatomic:** low energy nuclear structure and astrophysics, applied nuclear physics, high-energy cosmic-ray and neutrino physics, neutrinoless double beta decay,

**Condensed Matter and Materials Physics:** photovoltaics, thermoelectrics, plasmonics, materials discovery, thin-film semiconductors, amorphous materials, excitonic materials, optoelectronic materials, nanostructures and quantum dots, self-assembled systems, organic and soft condensed matter, x-ray diffraction, Raman spectroscopy, x-ray photoelectron spectroscopy, Auger spectroscopy, scanning probe microscopies, atom probe tomography, first principles condensed materials theory**,** electronic structure, topological disorder.

**Quantum Physics:** quantum chaos, strongly-correlated states, quantum computing, quantum information, quantum simulation, quantum many-body theory, quantum error correction, disorder in quantum materials, applied superconductivity, low-temperature physics, spintronics.

# GRADUATE CERTIFICATE IN OPTICS FOR ENGINEERING

## Program Requirements

The graduate certificate program in Optics for Engineering is targeted to train recent graduates or midcareer professionals with a Bachelor of Science degree in physics, chemistry, materials science, electrical or mechanical engineering, or other related fields. The program will provide them with a basic knowledge of optics and lasers so they can apply it to the challenges and demands of advanced technologies that use optical systems. the program offers students a number of electives to choose from and to tailor their education to their interest.

## Graduate Certificate Curriculum Requirements:

The certificate option consists of one core class, plus two additional electives, for a total of 9 credit hours. PHGN461 is considered a prerequisite for this certificate but is offered online in the summer, allowing students to easily fulfill this requirement. Students who have taken the equivalent of PHGN461 at a different institution can request to have this prerequisite waived.

## Graduate Certificate

| | | |
|---|---|---|
| PHGN581 | LASER PHYSICS | 3.0 |
| Electives | See Elective Listing | 6.0 |

## Coursework Details:

Students will need PHGN461 (or its equivalent) as a prerequisite for the certificate. This course is offered in the summer (online). PHGN581 is offered in the fall (in-person). Students will select two electives from the approved list below.

## Approved Electives (select two):

| | | |
|---|---|---|
| PHGN570 | FOURIER AND PHYSICAL OPTICS | 3.0 |
| PHGN566 | MODERN OPTICAL ENGINEERING | 3.0 |
| PHGN585 | NONLINEAR OPTICS | 3.0 |
| EENG528 | COMPUTATIONAL ELECTROMAGNETICS | |
| GPGN570 | APPLICATIONS OF SATELLITE REMOTE SENSING | 3.0 |
| EENG507 | INTRODUCTION TO COMPUTER VISION | 3.0 |
| EENG509 | SPARSE SIGNAL PROCESSING | 3.0 |
| EENG515 | MATHEMATICAL METHODS FOR SIGNALS AND SYSTEMS | 3.0 |

## Courses

**PHGN501. GRADUATE SEMINAR. 1.0 Semester Hr.**
(I) M.S. students will attend the weekly Physics Colloquium. Students will be responsible for presentations during this weekly seminar. See additional course registration instructions under Program Requirements above. 1 hour seminar; 1 semester hour.

**PHGN502. GRADUATE SEMINAR. 1.0 Semester Hr.**
(II) M.S. students will attend the weekly Physics Colloquium. Students will be responsible for presentations during this weekly seminar. See additional course registration instructions under Program Requirements above. 1 hour seminar; 1 semester hour.

**PHGN503. RESPONSIBLE CONDUCT OF RESEARCH. 1.0 Semester Hr.**
(II) This course introduces students to the various components of responsible research practices. Subjects covered move from issues related to professional rights and obligations through those related to collaboration, communication and the management of grants, to issues dealing with intellectual property. The course culminates with students writing an ethics essay based on a series of topics proposed by the course instructor. 1 hour lecture; 1 semester hour.
**Course Learning Outcomes**

- To be: (1) Exposed to and able to address a broad range of ethical issues that arise in a professional career in science and engineering. (2) Able to discuss such issues in the context of basic ethical theories. (3) Conscious of ethical ideals and commitments as they relate to science, society, enterprise, and environment.

**PHGN504. RADIATION DETECTION AND MEASUREMENT. 3.0 Semester Hrs.**
Physical principles and methodology of the instrumentation used in the detection and measurement of ionizing radiation. Prerequisite: none. 3 hours lecture; 3 semester hours.

**PHGN505. CLASSICAL MECHANICS I. 3.0 Semester Hrs.**
(I) Review of Lagrangian and Hamiltonian formulations in the dynamics of particles and rigid bodies; kinetic theory; coupled oscillations and continuum mechanics; fluid mechanics. Prerequisite: PHGN350 or equivalent. 3 hours lecture; 3 semester hours.

**PHGN507. ELECTROMAGNETIC THEORY I. 3.0 Semester Hrs.**
(II) To provide a strong background in electromagnetic theory. Electrostatics, magnetostatics, dynamical Maxwell equations, wave phenomena. Prerequisite: PHGN462 or equivalent and PHGN511. 3 hours lecture; 3 semester hours.

**PHGN511. MATHEMATICAL PHYSICS. 3.0 Semester Hrs.**
(I) Review of complex variable and finite and infinite-dimensional linear vector spaces. Sturm-Liouville problem, integral equations, computer algebra. Prerequisite: PHGN311 or equivalent. 3 hours lecture; 3 semester hours.

**PHGN515. GRADUATE LABORATORY. 3.0 Semester Hrs.**
Hands-on, laboratory skills are fundamental to all career pathways for physics graduates. This course is designed to provide first year graduate students with introductory skills necessary to carry out research in discipline specific laboratories – both in the physics department and post-graduate career settings. The course covers laboratory safety and current experiment best practices. Instruments common in academia, industry, and national labs are reviewed in their function and properties. Students will review experimental data analysis, error analysis, and error propagation concepts before applying them to experiments. Two weeks are dedicated to a student-facilitator shared experiment focusing on lock-in detection where students will learn the structure of note taking and grading. Students will then use what they learned in the lectures and tutorials to perform three experiments they help design. Although experimental results are expected and required, the course will emphasize scientific note taking and thought process over results. The experiments are intentionally open ended so students will have to think critically about their experimental methods, take detailed notes, and use trial-and-error. Thought process will be operationally defined through tinkering, resilience, teamwork, and communication.
**Course Learning Outcomes**

- Learning Outcomes

**PHGN519. FUNDAMENTALS OF QUANTUM INFORMATION. 3.0 Semester Hrs.**
This course serves as a broad introduction to quantum information science, open to students from many backgrounds. The basic structure of quantum mechanics (Hilbert spaces, operators, wavefunctions, entanglement, superposition, time evolution) is presented, as well as a number of important topics relevant to current quantum hardware (including oscillating fields, quantum noise, and more). Finally, we will survey the gate model of quantum computing, and study the critical subroutines which provide the promise of a quantum speedup in future quantum computers. Prerequisite: MATH332 (linear algebra) or an equivalent linear algebra course.
**Course Learning Outcomes**

- After completing this course, students will be able to: 1. Construct Hilbert spaces, operators, wavefunctions and predict the outcome of measurements
- 2. Identify the key ways in which quantum mechanics differs from classical mechanics: entanglement and superposition
- 3. Simulate time evolution in quantum systems
- 4. Diagonalize simple quantum Hamiltonians and predict their spectra
- 5. Simulate oscillating fields in quantum systems
- 6. Implement simple calculations using the gate model of quantum computing. They will also learn how to use ancilla qubits, and how to construct arbitrary operations from one- and two-qubit gates
- 7. Identify mechanisms for a quantum speedup in quantum algorithms, learned through a survey of some of the most famous ones

**PHGN520. QUANTUM MECHANICS I. 3.0 Semester Hrs.**
(II) Schroedinger equation, uncertainty, change of representation, one-dimensonal problems, axioms for state vectors and operators, matrix mechanics, uncertainty relations, time-independent perturbation theory, time-dependent perturbations, harmonic oscillator, angular momentum; semiclassical methods, variational methods, two-level system, sudden and adiabatic changes, applications. Prerequisite: PHGN511 and PHGN320 or equivalent. 3 hours lecture; 3 semester hours.

**PHGN521. QUANTUM MECHANICS II. 3.0 Semester Hrs.**
(I) Review of angular momentum, central potentials and applications. Spin; rotations in quantum mechanics. Formal scattering theory, Born series, partial wave analysis. Addition of angular momenta, Wigner-Eckart theorem, selection rules, identical particles. Prerequisite: PHGN520. 3 hours lecture; 3 semester hours.

**PHGN526. QUANTUM ENGINEERING SEMINAR (FALL). 1.0 Semester Hr.**
The Quantum Engineering Seminar Series offers graduate students an opportunity to engage with leading professionals from the quantum industry. Through a series of guest lectures, students will explore cutting-edge developments in quantum technology, including quantum computing, sensing, materials, and communications. The course emphasizes professional development by fostering networking skills, enhancing career readiness, and encouraging interdisciplinary collaboration. Students will be encouraged to develop a ‘portfolio’ with summaries of discussions, follow up correspondence with speakers, and reflections on how they see their future careers in this field. This seminar series aligns with the Mines@150 mission, preparing students to become innovative leaders in the evolving field of quantum engineering.
**Course Learning Outcomes**

- Students will gain an understanding of current trends, challenges, and opportunities in the quantum industry directly from leading professionals.
- Students will develop the ability to build and maintain professional networks with industry leaders and peers in the quantum engineering field.
- Students will be able to identify how theoretical concepts in quantum engineering are applied in various industry sectors.
- Students will enhance their awareness of the skills and expertise required by employers in the quantum industry, improving their job readiness.
- Students will cultivate an entrepreneurial mindset by analyzing how quantum technologies can be commercialized and brought to market.
- Students will improve their ability to engage in meaningful discussions with industry experts, enhancing their professional communication skills.

**PHGN527. QUANTUM ENGINEERING SEMINAR (SPRING). 1.0 Semester Hr.**
The Quantum Engineering Seminar Series offers graduate students an opportunity to engage with leading professionals from the quantum industry. Through a series of guest lectures, students will explore cutting-edge developments in quantum technology, including quantum computing, sensing, materials, and communications. The course emphasizes professional development by fostering networking skills, enhancing career readiness, and encouraging interdisciplinary collaboration. Students will be encouraged to develop a ‘portfolio’ with summaries of discussions, follow up correspondence with speakers, and reflections on how they see their future careers in this field. This seminar series aligns with the Mines@150 mission, preparing students to become innovative leaders in the evolving field of quantum engineering.
**Course Learning Outcomes**

- Students will gain an understanding of current trends, challenges, and opportunities in the quantum industry directly from leading professionals.
- Students will develop the ability to build and maintain professional networks with industry leaders and peers in the quantum engineering field.
- Students will be able to identify how theoretical concepts in quantum engineering are applied in various industry sectors.
- Students will enhance their awareness of the skills and expertise required by employers in the quantum industry, improving their job readiness.
- Students will cultivate an entrepreneurial mindset by analyzing how quantum technologies can be commercialized and brought to market.
- Students will improve their ability to engage in meaningful discussions with industry experts, enhancing their professional communication skills.

**PHGN530. STATISTICAL MECHANICS. 3.0 Semester Hrs.**
(I) Review of thermodynamics; equilibrium and stability; statistical operator and ensemblesl ideal systems; phase transitions; non-equilibrium systems. Prerequisite: PHGN341 or equivalent and PHGN520. Co-requisite: PHGN521. 3 hours lecture; 3 semester hours.

**PHGN532. LOW TEMPERATURE MICROWAVE MEASUREMENTS FOR QUANTUM ENGINEERING. 3.0 Semester Hrs.**
The goal of the course is to provide hands on training in high-frequency, low-temperature measurements which are requisite for quantum information applications. This course introduces the fundamentals of high-frequency measurements, the latest techniques for accuracy-enhanced automated microwave measurements, low-temperature measurement techniques, low noise measurements, and common devices used in quantum information. The course will have three modules. The first module, basics of electronic measurements, will include chip layout, power measurements, ground loop testing, impedance measurements, noise fundamentals, cable and device fabrication and care. The second module, high frequency measurements, will include measurements of basic scattering parameters, accuracy enhancement and calibration, transmission line, amplifier, and oscillator characterization including noise measurements. The third module, low-temperature measurements, will cover critical parameters for superconductors and Josephson junctions, measurements of superconducting resonators, characterization of low-temperature electronic elements including amplifiers. At the end of this course the students will know how to use network analyzers, spectrum analyzers, cryostats, the software Eagle for chip design, amplifiers, and filters.
**Course Learning Outcomes**

- 1. Describe key RF, wireless and microwave measurement parameters
- 2. Understand how to use a range of RF, wireless and microwave test equipment
- 3. Reduce the risk of expensive test equipment damage, repair costs and downtime
- 4. Understand how to correctly perform common RF and microwave measurements
- 5. Understand the basics of low-temperature measurements including critical parameters for superconductors and Josephson junctions, as well as characterization of low-temperature electronic elements
- 6. Better utilize test and measurement equipment features and functionality
- 7. Develop improved problem solving capability due to better understanding

**PHGN535. INTERDISCIPLINARY SILICON PROCESSING LABORATORY. 0-3 Semester Hr.**
Equivalent with CBEN435,CBEN535,CHEN435,CHEN535,MLGN535,PHGN435,
(II) Explores the application of science and engineering principles to the fabrication and testing of microelectronic devices with emphasis on specific unit operations and interrelation among processing steps. Teams work together to fabricate, test, and optimize simple devices. Prerequisite: none. 1 hour lecture, 4 hours lab; 3 semester hours.

**PHGN542. SOLID STATE DEVICES AND PHOTOVOLTAIC APPLICATIONS. 3.0 Semester Hrs.**
(II) An overview of the physical principles involved in the characterization, and operation of solid state devices. Topics will include: semiconductor physics, electronic transport, recombination and generation, intrinsic and extrinsic semiconductors, electrical contacts, p-n junction devices (e.g., LEDs, solar cells, lasers, particle detectors); other semiconductor devices (e.g., bipolar junction transistors and field effect transistors and capacitors). There will be emphasis on optical interactions and application to photovoltaic devices. Prerequisite: PHGN440 or equivalent. 3 hours lecture; 3 semester hours.

**PHGN545. QUANTUM MANY-BODY PHYSICS. 3.0 Semester Hrs.**
This course offers an introduction to quantum many-body physics in a modern approach from the perspectives of quantum information science. Starting from the difference between classical and quantum correlations, this course introduces composite quantum systems and the concept of entanglement as the central theme in quantum many-body physics. A system of many spin-1/2s is then presented as the paradigmatic quantum many-body system, opening the realm of quantum phase transitions and quantum simulation experiments. Next, systems of non-interacting bosons or fermions are examined using the powerful canonical transformation. To understand what happens when particles interact, the well-known Hubbard model is brought in, together with its importance in quantum materials. Finally, topological ordered quantum matter is introduced and explained via the structure of quantum entanglement. The application of topological order to quantum computing will also be mentioned.
**Course Learning Outcomes**

- In this course, students will learn to: 1. Describe quantum systems of many individual degrees of freedom.
- 2. Comprehend the concept of quantum entanglement and quantum correlations.
- 3. Analyze quantum phases and phase transitions of a typical quantum many-body model, such as a transverse-field Ising model.
- 4. Solve the energy spectrum of non-interacting fermions and bosons.
- 5. Investigate the qualitative effects of typical interactions among particles.
- 6. Become familiar with quantum simulation experiments.
- 7. Understand topological order of quantum matter and its relation to quantum computing.

**PHGN550. NANOSCALE PHYSICS AND TECHNOLOGY. 3.0 Semester Hrs.**
An introduction to the basic physics concepts involved in nanoscale phenomena, processing methods resulting in engineered nanostructures, and the design and operation of novel structures and devices which take advantage of nanoscale effects. Students will become familiar

with interdisciplinary aspects of nanotechnology, as well as with current nanoscience developments described in the literature. Prerequisites: PHGN320, PHGN341, co-requisite: PHGN462. 3 hours lecture; 3 semester hours.

**PHGN566. MODERN OPTICAL ENGINEERING. 3.0 Semester Hrs.**
Provides students with a comprehensive working knowledge of optical system design that is sufficient to address optical problems found in their respective disciplines. Topics include paraxial optics, imaging, aberration analysis, use of commercial ray tracing and optimazation, diffraction, linear systems and optical transfer functions, detectors, and optical system examples. 3 hours lecture; 3 semester hours.

**PHGN570. FOURIER AND PHYSICAL OPTICS. 3.0 Semester Hrs.**
This course addresses the propagation of light through optical systems. Diffraction theory is developed to show how 2D Fourier transforms and linear systems theory can be applied to imaging systems. Analytic and numerical Fourier and microscopes, spectrometers and holographic imaging. They are also applied to temporal propagation in ultrafast optics. Prerequisite: PHGN462 or equivalent. 3 hours lecture; 3 semester hours.

**PHGN581. LASER PHYSICS. 3.0 Semester Hrs.**
Theory, modeling, and experimental work with: absorption and emission of light from atoms, Gaussian beams, optical resonator theory and design, laser oscillation and pulsing dynamics, introduction to nonlinear optics and ultrafast pulses. Full scope of PHGN480 with more advanced homework, experimental analysis/modeling, and final project.
**Course Learning Outcomes**

- Be able to explain the interaction of light and quantum transitions, including the origin of gain in different media
- Be able to derive and solve rate equations to describe the balance of stored energy in the gain medium and in the circulating light field in the resonator
- Be able to use matrix methods to calculate the propagation of light as rays and as Gaussian beams and how to use these matrices to design optical resonators
- Build and apply a quantitative model of laser oscillation to a real laser system
- Be able to experimentally align and characterize simple lasers and use advanced diagnostic techniques and analyzis
- Be able to use the techniques developed in the course to analyze a published laser system design

**PHGN585. NONLINEAR OPTICS. 3.0 Semester Hrs.**
An exploration of the nonlinear response of a medium (semiclassical and quantum descriptions) and nonlinear wave mixing and propagation. Analytic and numeric techniques to treat nonlinear dynamics are developed. Applications to devices and modern research areas are discussed, including harmonic and parametric wave modulation, phase conjugation, electro-optic modulation. Prerequiste: PHGN462 or equivalent, PHGN520. 3 hours lecture; 3 semester hours.

**PHGN590. NUCLEAR REACTOR PHYSICS. 3.0 Semester Hrs.**
Bridges the gap between courses in fundamental nuclear physics and the practice of electrical power production using nuclear reactors. Review of nuclear constituents, forces, structure, energetics, decay and reactions; interaction of radiation with matter, detection of radiation; nuclear cross sections, neutron induced reactions including scattering, absorption, and fission; neutron diffusion, multiplication, criticality; simple reactor geometries and compositions; nuclear reactor kinetics and control; modeling and simulation of reactors. Prerequisite: PHGN422.

**PHGN597. SUMMER PROGRAMS. 0-6 Semester Hr.**

**PHGN598. SPECIAL TOPICS. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**PHGN598. SPECIAL TOPICS. 0-6 Semester Hr.**

**PHGN598. SPECIAL TOPICS. 0-6 Semester Hr.**

**PHGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: Independent Study form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**PHGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

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**PHGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**PHGN601. ADVANCED GRADUATE SEMINAR. 1.0 Semester Hr.**
(I) Ph.D. students will attend the weekly Physics Colloquium. Students will be responsible for presentations during this weekly seminar. See additional course registration instructions under Program Requirements above. 1 hour seminar; 1 semester hour.

**PHGN602. ADVANCED GRADUATE SEMINAR. 1.0 Semester Hr.**
(II) Ph.D. students will attend the weekly Physics Colloquium. Students will be responsible for presentations during this weekly seminar. See additional course registration instructions under Program Requirements above. 1 hour seminar; 1 semester hour.

**PHGN608. ELECTROMAGNETIC THEORY II. 3.0 Semester Hrs.**
Spherical, cylindrical, and guided waves; relativistic 4-dimensional formulation of electromagnetic theory. Prerequisite: PHGN507. 3 hours lecture; 3 semester hours. Offered on demand.

**PHGN612. MATHEMATICAL PHYSICS II. 3.0 Semester Hrs.**
Continuation of PHGN511. Prerequisite: none. 3 hours lecture; 3 semester hours. Offered on demand.

**PHGN623. NUCLEAR STRUCTURE AND REACTIONS. 3.0 Semester Hrs.**
The fundamental physics principles and quantum mechanical models and methods underlying nuclear structure, transitions, and scattering reactions. Prerequisite: PHGN521. 3 hours lecture; 3 semester hours. Offered on demand.

**PHGN624. NUCLEAR ASTROPHYSICS. 3.0 Semester Hrs.**
The physical principles and research methods used to understand nucleosynthesis
and energy generation in the universe. Prerequisite: none. 3 hours lecture; 3 semester hours. Offered on demand.

**PHGN641. ADVANCED CONDENSED MATTER PHYSICS. 3.0 Semester Hrs.**
Provides working graduate-level knowledge of applications of solid state physics and important models to crystalline and non-crystalline systems in two and three dimensions. Review of transport by Bloch electrons; computation, interpretation of band structures. Interacting electron gas and overview of density functional theory. Quantum theory of optical

properties of condensed systems; Kramers-Kronig analysis, sum rules, spectroscopies. Response and correlation functions. Theoretical models for metal-insulator and localization transitions in 1, 2, 3 dimensions (e.g., Mott, Hubbard, Anderson, Peierls distortion). Boltzmann equation. Introduction to magnetism; spin waves. Phenomenology of soft condensed matter: order parameters, free energies. Conventional superconductivity.
Prerequisites: PHGN440 or equivalent, PHGN520, PHGN530. 3 hours lecture; 3 semester hours.

**PHGN698. SPECIAL TOPICS. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**PHGN699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: Independent Study form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**PHGN699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

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**PHGN699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**PHGN707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.**
(I, II, S) Research credit hours required for completion of a Masters-level thesis or Doctoral dissertation. Research must be carried out under the direct supervision of the student's faculty advisor. Variable class and semester hours. Repeatable for credit.

## Professors

Lincoln D. Carr

Patrice Genevet

Charles G. Durfee III

Uwe Greife

Mark T. Lusk

Frederic Sarazin, Department Head

Jeff A. Squier

Eric S. Toberer, Director of Materials Science

Lawrence R. Wiencke

## Associate Professors

Daniel Adams

Zhexuan Gong

Eliot Kapit

Kyle G. Leach

Timothy R. Ohno

Meenakshi Singh

Jeramy D. Zimmerman

## Assistant Professors

Eric Mayotte

Wouter Van de Pontseele

## Teaching Professors

Kristine E. Callan

Alex T. Flournoy (deceased)

Patrick B. Kohl

H. Vincent Kuo, Assoc Dept Head, Director of UG Studies

Todd G. Ruskell

Charles A. Stone

## Teaching Associate Professor

Emily M. Smith

## Teaching Assistant Professors

Victoria (Tori) Borish

Laith Haddad

Alysa (Ly) Malespina

## Research Professor

Wendy Adams Spencer

## Research Associate Professor

K. Xerxes Steirer

## Research Assistant Professors

Kamil Ciesielski

Serena M. Eley

P. David Flammer

## Professors Emeriti

F. Edward Cecil

Reuben T. Collins

Thomas E. Furtak

Frank V. Kowalski

John Scales

P. Craig Taylor

John Trefny, President Emeritus

Don L. Williamson

### Associate Professors Emeriti

David M. Wood

# Interdisciplinary Programs

# Advanced Energy Systems

## Degrees Offered

- Master of Science in Advanced Energy Systems (non-thesis)
- Doctor of Philosophy in Advanced Energy Systems

## Program Description

The Advanced Energy Systems (AES) graduate engineering degree program is an interdisciplinary program designed in collaboration with researchers at the National Renewable Energy Laboratory (NREL). The rigorous AES graduate program integrates the strengths of both institutions to offer MS and PhD students unique educational and research experiences.

The program is designed to prepare energy professionals and researchers to address a variety of complex problems associated with the energy transition. The breadth of potential research topics is considerable and spans topical areas including biofuels, hydrogen and electrochemical devices, solar, wind, building energy systems, grid modernization, energy security and resilience. A common thread is the application of science and engineering fundamentals to develop effective solutions in any of the many dimensions needed to secure a sustainable energy future.

AES students are part of a cohort-based community of students, Mines faculty, and NREL technical staff that fosters professional development, cross-disciplinary thinking and systems understanding of the grand energy challenges. Educational emphases intermingle fundamental STEM coursework with techno-economic and environmental impact analysis to broaden student understanding of the entire energy supply and utilization value chain.

Graduates of the AES program are uniquely situated to enter the workforce in roles supporting advanced energy innovation and energy systems research and integration in government, academia, non-profit organizations, and the private sector.

## Program Description

The Advanced Energy Systems graduate engineering degree program offers the Master of Science and the Doctor of Philosophy of Advanced Energy Systems. The master's program is a course-based, non-thesis program designed to prepare graduates for diverse careers in industry, government, and non-profit organizations or for additional graduate study at the PhD level. The PhD degree program prepares graduates for careers in academia, industry, government, or non-profit leadership.

Prospective AES students apply to enter the Advanced Energy Systems program through Mines' Graduate Admissions. Final admissions decisions are made by AES after a holistic admissions review. MS and PhD curricula have overlap where new students in both programs complete three core courses as part of the degree program. Three core courses are required for all MS-NT students and all PhD students. Two additional core courses are required of all PhD students.

The following information provides detail on each of the degree options.

## Mines' Combined Undergraduate/Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

## Program Requirements

*Admitted Students:* The Advanced Energy Systems graduate admissions committee may require that any admitted student complete undergraduate remedial coursework to overcome technical deficiencies. Such coursework may not count toward the graduate degree. The AES admissions committee will decide whether to recommend regular or provisional admission. In accordance with Mines institutional policy, all AES students are required to maintain a minimum cumulative GPA of 3.0.

*Transfer Courses*: Graduate-level courses taken at other universities for which a grade equivalent to a B or better was earned may be considered for transfer credits for the AES MS and PhD degree program. Approval must be granted after all appropriate documentation has been submitted to the AES program director who will conduct a review of the transfer petition. Review of transfer credits is based on the relevance of the coursework to AES and the recency of completion for any transfer credits requested. Some exceptions may apply, however, coursework completed more than five years from AES enrollment will not be considered. Transfer credits may not have been used as credit toward a bachelor's degree. For the MS degree, no more than 9 credits may transfer. For the PhD degree, up to 24 credits may be transferred. Students who enter the PhD program with a thesis-based master's degree from an accredited institution may request to transfer up to 36 hours in recognition of the coursework and research completed for that degree. All transfer credits are to be submitted in the first semester of enrollment for program consideration and review for recency and AES relevance.

## Master of Science – Non-Thesis Degree Requirements

The AES Master of Science, Non-Thesis (MS-NT) is a stand-alone graduate engineering degree wherein students are self-supported or supported by industry or other outside sources. The AES MS-NT degree is course-based and targeted for students interested in professional careers in industry, government, or non-governmental positions. Students enrolled in the MS program do not participate in the three 600 level PhD core. The MS-NT degree requires 30 credit hours of coursework as stipulated below. Approved elective credit hours must be taken at the graduate level at Mines and are reviewed to ensure that they form a coherent focus for an in-depth energy science and engineering study.

*Advisor:* All AES MS students will have an advisor to guide and monitor their academic plan and progress toward graduation.

## MS Non-Thesis Degree

| | | |
|---|---|---|
| ENGY501 | PHYSICS OF ENERGY RESOURCES & CONVERSION | 3.0 |
| ENGY502 | ENERGY FOR TRANSPORTATION | 3.0 |
| ENGY503 | ENERGY & POWER SYSTEMS INTEGRATION | 3.0 |
| Economics | Student must select one graduate-level Economics course from the approved program list. | 3.0 |
| Technical Electives | Technical Electives (STEM Courses approved by Advisor and Program Director) | 12-18 |
| Economics or Policy | Student may select up to two (2) courses from the approved program list. | 0-6 |
| Total | | 30.0 |

## Advanced Energy Systems Doctor of Philosophy Degree Requirements

The PhD degree in Advanced Energy Systems requires 72 total credits. A minimum of 36 credits of coursework and 36 credits of research credits must be completed. A minimum of 15 of the 36 credits of required coursework must be taken at Colorado School of Mines as three core courses plus the three 600-level PhD courses.

The AES PhD program is designed as a full-time, four-year program of study for students having completed a minimum of a bachelor's degree in Science or Engineering. In accordance with all other graduate programs at Mines, a minimum of two semesters of full-time enrollment is required and follows the program as detailed below.

## PhD Degree Requirements

| | | |
|---|---|---|
| ENGY501 | PHYSICS OF ENERGY RESOURCES & CONVERSION | 3.0 |
| ENGY502 | ENERGY FOR TRANSPORTATION | 3.0 |
| ENGY503 | ENERGY & POWER SYSTEMS INTEGRATION | 3.0 |
| ENGY691 | INTRODUCTION TO RESEARCH METHODS IN THE ENERGY SCIENCES | 3.0 |
| ENGY692 | PROJECT FOCUSED RESEARCH IN ENERGY SCIENCE & TECHNOLOGY | 3.0 |
| Economics | Student must select one graduate-level Economics course from the approved program list | 3.0 |
| Technical Electives | Technical Electives (STEM courses approved by Advisor and Program Director) | 15-18 |
| Economics or Policy Elective | Student may select one graduate-level Economics or Policy course from the approved program list | 0-3 |
| ENGY693 | AES GRADUATE STUDENT SEMINAR (AES PhD Seminar: Students are required to register every fall and spring. Students may use up to 3 credits towards the degree.) | 0-3 |
| ENGY707 | GRADUATE THESIS | 36.0 |
| Total | | 72.0 |

*Timeline and Milestones:* PhD students must make adequate progress and reach appropriate milestones toward their degree by working with their faculty advisor and thesis committee. The AES Program has adopted a standard Mines PhD timeline that outlines milestones that students are expected to reach on a semester-by-semester basis. Each milestone is listed here with detail.

| PhD MILESTONE | EXPECTED TIMELINE |
|---|---|
| Select a permanent advisor | By Second semester |
| Complete the PhD qualifying examination | In June of first year of enrollment |
| Establish a dissertation committee | By Fourth semester |
| Complete all core curriculum course requirements | Fourth semester |
| Present research proposal; Submit Degree Audit and Admission to Candidacy forms | Fifth semester or earlier |
| Present a preliminary defense | 9-12 months before dissertation defense |
| Present a dissertation defense | End of Year Four |

*Funding:* Students admitted to the AES PhD program are fully funded. Typically, first-year funding is provided by the Program. Subsequent funding is provided for the subsequent three years by the research group to which the PhD student is aligned.

*Advisor : Preliminary and permanent:* AES students are assigned a first-year advisor to guide and monitor their progress toward the qualifying exam. First-year PhD advisors are assigned based on the student's emergent research interests stated at the time of application. By the end of the first year, students select a permanent academic advisor closely aligned with their academic and research interests, who will serve to guide, monitor, and evaluate their progress toward the final dissertation defense. A unique aspect of the AES program is the NREL mentors who are engaged to support the student's research efforts. While the lead advisor is the Mines academic graduate faculty, the NREL research provides additional guidance for the student's research agenda.

*Qualifying Exam:* All AES PhD students are required to pass a qualifying exam given at the end of the second semester of enrollment. PhD students must have earned a minimum grade point average of 3.3 and have completed the first-year required core courses to sit for the qualifying exam. The AES program director oversees the process and ensures that the exam is administered fairly.

In accordance with other PhD programs at Mines, the purpose of the qualifying exam is to assess attributes expected of a successful PhD student, including:

- Ability to review, synthesize and apply fundamental concepts.
- Creative and technical ability to propose research solutions to solve open-ended and challenging problems.
- Technical Communication Skills.

The AES qualifying exam requires students to develop a hypothesis-driven research proposal on the student's topic of interest in consultation with the academic advisor and research mentor. Students submit their

research proposal to a panel of reviewers to include the AES program directors and one invited subject matter expert. The student presents the research proposal and, similar to the thesis-proposal process, answers a series of questions from the panel.

Exam results of pass, conditional pass, or fail are provided to the students immediately following the oral defense portion of the exam. Written feedback is provided within three days of the exam. Students who fail the exam may be offered one additional opportunity to pass the exam before the start of the third semester. Students who fail on the second attempt may be offered an opportunity to complete the MS-NT as the terminal degree and may be provided one immediate final semester of support to do so.

*Thesis Committee:* Upon successful completion of the qualifying exam and in consultation with the Mines academic advisor, each PhD student will assemble a five-person thesis committee that includes: the student's Mines academic advisor and NREL mentor (as the student's co-advisor); two additional Mines faculty who have a science and/or engineering background; and a fifth member of the committee who serves as the chair and is not in the home department of the advisor. Additional committee members with specific expertise may be allowed. If there is no NREL mentor, the committee composition may constitute four members, minus the co-advisor. The AES program director must review and approve all committee requests prior to submission to the Office of Graduate Studies.

*Research Proposal:* After passing the qualifying exam, the PhD student will prepare a written research proposal for the dissertation and present it formally to the dissertation committee, which will have been selected by the student in consultation with the Mines academic advisor and approved by the program director.

A written research proposal document will be provided to the committee in advance of the presentation with the expectation of achieving the following:

- Demonstrate a knowledge of background and motivation of the research problem being undertaken as embodied by a review of the relevant literature.
- Enumerate specific aims and/or hypotheses.
- Identify preliminary techniques, materials, and specific measurements for the proposed research project.
- Explain clearly the scientific merit (value added) of the proposed work.
- Provide a general idea of the timeline for the research program.
- Specify potential publications and presentations that may arise from the work.

The student and the advisor must convene a meeting of the full dissertation committee in which the student gives an oral summary of their written proposal in a 30- to 45-minute presentation. This research proposal gives the committee an early chance to discuss the work and to help the student more clearly define the work and identify the salient aspects. The research proposal presentation should ideally occur before the beginning of year 3 of the program. The research proposal must be completed before admission to candidacy.

*Degree Audit and Admission to Candidacy:* PhD students must complete the Degree Audit form by the posted deadlines and the Admission to Candidacy form by the first day of classes of the semester in which they want to be considered eligible for reduced registration.

Additionally, full-time PhD students must complete the following requirements within the first two calendar years after enrolling in the AES PhD program:

- Have a thesis committee appointment form on file in the Graduate Office.
- Complete all prerequisite and core curriculum course requirements.
- Demonstrate adequate preparation for and satisfactory ability to conduct doctoral research.
- Be admitted into full candidacy for the degree.

*Preliminary Defense:* Prior to the final dissertation defense, the PhD student will make an oral presentation to the student's committee to summarize research accomplishments and remaining goals and work plan. This meeting serves as a final check to assess if the student's progress is on schedule for graduation. This meeting should present a preliminary document that will likely evolve and expand into the dissertation. The preliminary document should include basic literature review, methodologies used, results to date, and an estimated timeline for remaining work. The student must give no more than a 45-minute presentation that summarizes the work already accomplished, including their relevant publication(s) and a proposed plan of the work needed to culminate in a formal defense and graduation. The committee will provide feedback and, as necessary, revisions to the proposed work plan such that its completion should lead to a successful dissertation defense and publication record in a realistic time frame. The time period between the research proposal and the preliminary defense can span a few years, but the preliminary defense should take place 12 months and no less than six months prior to the date of dissertation defense.

Publications and Presentations: The required and recommended journal publications for PhD students prior to graduation are listed below. Students wanting to defend before meeting these requirements must submit a one-page petition with a reasonable explanation to the AES program director.

*Journal Publications: Required:* Minimum of two first-author paper accepted or published (DOI is required) in a peer-reviewed journal (recognized as high quality in the research field), before Dissertation Defense. *Recommended:* Three or more first-author papers accepted or published in peer-reviewed journals. More than three first author journal publications are recommended for students interested in academic positions.

*Presentations — Required:* Minimum of one research presentation (poster or podium) at an external technical conference before the dissertation defense. Minimum of three presentations in the AES graduate seminar or equivalent (such as campus-wide graduate student research conference, research sponsor meetings, or additional conference presentations) during PhD program. *Recommended:* Two or more conference presentations (poster or podium) before the dissertation defense in which the student is the first author on these presentations. Numerous conference presentations are strongly encouraged to establish a reputation amongst researchers in a field for students interested in academic positions.

*Thesis Defense:* At the conclusion of their PhD program, students are required to make a formal presentation and defense of their thesis research. A student must "pass" this defense to earn a PhD degree. The dissertation document should be submitted to the dissertation committee at least 10 days prior to the defense. The committee will perform a post-presentation review of the dissertation, technical contributions, and publications with the student. The committee may request revisions to

the dissertation and additional work that requires subsequent review by the advisor and or the committee.

*Unsatisfactory Progress*: To ensure that a student receives proper feedback if progress toward the preliminary defense or the dissertation defense is not satisfactory, the advisor must provide the student and the committee a brief, written progress evaluation. If the student's progress is unsatisfactory such that the advisor gives them a PRU grade for research credits, the student will go on academic probation as outlined in the graduate bulletin.

## Courses

**ENGY501. PHYSICS OF ENERGY RESOURCES & CONVERSION. 3.0 Semester Hrs.**
This course will provide successful students a quantitative understanding of how fossil, renewable and nuclear energy resources are harnessed to electric power. A foundational underpinning will be the thermodynamics of energy conversion, using fundamental principles and language bridging physics, chemistry and engineering. Examples will be taken from both established and emerging technologies spanning solar, nuclear, wind fossil fuel and bioenergy conversion. Students will also learn how to analyze electricity generation, transmission, and grid-scale storage systems with a focus on the U.S. as a framework for analyzing other developing markets.
**Course Learning Outcomes**

- With respect to all energy resources: 1. Articulate in writing, major quantitative trends and forces behind the evolution of fossil, nuclear, and renewable energy resource utilization of the U.S.; 2. Demonstrate knowledge of how permitting, regulations, markets, and environmental impact drive investment for utility-scale power generation; 3. Compare quantitatively the levelized cost of electricity, major environmental impacts, and water usage for electricity generation from fossil, renewable, and nuclear resources;
- With respect to solar resources: 4. Quantitatively assess solar resources in the U.S. and the challenges (economic and grid-related) to increase solar penetration on the electric grid; 5. Quantify advances in solar photovoltaic technology in terms of cost and efficiency and estimate trends for levelized costs of electricity for photovoltaics over the next 10 years; 6. Evaluate levelized cost of electricity for concentrating solar power with thermal energy storage for utility scale applications;
- With respect to wind, geothermal, and hydroelectric resources 7. Quantitatively assess wind, geothermal, and hydropower resources in the U.S. and opportunities for increased penetration in the electric utility grid; 8. Perform basic analysis of levelized cost of electricity as a function of wind conditions, turbine size, and turbine location based on weather conditions;
- With respect to biomass resources 9. Compare different biomass resources for fuels and power plants and their economic viability relative to other fuel and power resources;
- With respect to fossil fuel resources: 10. Demonstrate quantitative knowledge of coal and natural gas extraction from an unconventional reservoir and evaluate costs of extraction and delivery of fossil fuel resources; 11. Analyze basic thermodynamic performance and operation of present-day Rankine, Brayton, and combined cycle power plants running on fossil fuel inputs including coal;
- With respect to nuclear resources: 12. Demonstrate basic knowledge of differences in the major nuclear power plant technologies in terms of conversion efficiencies and waste streams;
- With respect to the current utility-scale electric grid: 13. Evaluate the cost and performance of power generation sources and grid-scale storage technology and assess the impact on energy markets and renewable energy penetration; 14. Assess the impact of storage on transition of the US power system and future research and development needs; 15. Perform real-time electricity pricing calculation for a selected electricity market in U.S.;
- With respect to advanced energy grids, distributed power, and energy storage: 16. Articulate advances in distributed power and advanced controls and their impact upon grid operation and utility markets in a smart grid framework for the U.S.; 17. Identify the challenges and risks arises due to cyber-security in a smart grid and articulate awareness of the essential tools used to secure grid infrastructure; 18. Evaluate energy storage technologies and compare their economic feasibility, round-trip efficiency, and potential capacity for distributed power applications.

**ENGY502. ENERGY FOR TRANSPORTATION. 3.0 Semester Hrs.**
(I) This course focuses on multiple aspects of current and proposed transportation technologies to analyze the challenges and opportunities of moving toward more sustainable transportation infrastructure. This course is designed to train students to develop analytical skills and to use computational tools for evaluating performance and environmental impacts of various vehicle and fueling technologies. Successful students will develop a basis for assessing energy resource requirements and environmental concerns within the context of technical performance, policy frameworks, and social perspectives. The course will include the following topics: travel demand and travel modes; transportation technologies; fossil-fuel and electric power plants and associated fuels; emissions (CO2 and pollutants) formation and impacts on air quality, climate, and human health; national/international transportation policy; and transportation planning. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- With respect to the oil and gas distribution systems: 1. Perform assessment on the oil and natural gas distribution network in terms of sensitivity of fuel prices to key economic, environmental and political factors; 2. Evaluate the midstream and downstream production of U.S. liquid fuels; 3. Articulate the risks associate with fossil fuel production and utilization and the associated environmental impacts; 4. Assess the impact of vehicle electrification on oil and gas markets;
- With respect to aerospace and shipping transportation and fuels: 5. Assess the efficiency of all types of vehicle transportation technology and major historical trends with respect to fuel demands for various transportation sectors; 6. Identify fuel(s) needed for aircraft propulsion and assess trends for efficiency and reduced emissions from large aircraft; 7. Assess fuel utilization for large-scale shipping of goods with ships, trains, and large trucks and evaluate potential paradigm shifts in heavy transportation; 8. Perform well-to-wheel analysis on at least two large-vehicle technology platforms and assess the feasibility of alternative fuel sources and/or energy carriers;
- With respect to automotive transportation, fuels, and alternative energy carriers: 9. Assess internal combustion engine technology performance and emissions from a historical perspective and with respect to current-day trends; 10. Evaluate electric vehicle performance including battery and charging technologies including with respect to costs and energy demands for selected transportation sectors; 11. Articulate opportunities and challenges of a hydrogen- or biomass/waste gasification to support fueling infrastructure for a region of the U.S.; 12. Perform well-to-wheel analysis on at least two automotive technology platforms and assess their impact on energy usage and emissions; 13. Conduct technoeconomic analysis

of hydrogen as an energy carrier for the transportation sector and the potential for fuel cells in vehicles; 14. Identify the challenges and risks arises due to cyber-security in an electrified transportation system, including autonomous systems.

**ENGY503. ENERGY & POWER SYSTEMS INTEGRATION. 3.0 Semester Hrs.**
This course will provide students with basic skills to analyze the operation and evolution of the electric grid and electricity utilization with a particular emphasis on trends toward increased renewable energy penetration. The course will develop students' analytical skills to evaluate how electricity generation, transmission, distribution and storage are managed and controlled. Successful students will gain a basic understanding of electromechanical machines for power conversion and AC power distribution as well as renewable energy sources and battery systems with DC storage. The course will introduce students to how efficient energy utilization and demand response management impact the electric grid performance and electricity markets. An emphasis on managing energy loads in buildings, the commercial sector, and energy-intensive manufacturing will expose students to system-level modeling tools that can assess how to manage power demands with transient power generation and market forces. The course will also address the integrated nature of energy systems with an emphases on connections to water demands and on risks arising due to cybersecurity and resiliency threats facing the electric grid.
**Course Learning Outcomes**

- With respect to the current broad trends in energy utilization in buildings : 1. Assess quantitative trends and major forces behind the past and future evolution with respect to energy utilization in residential buildings, commercial sector, and major industries; 2. Analyze cooling and heating loads of residential buildings and commercial buildings as a function of HVAC technology and geographical location; 3. Evaluate historical trends and new technologies in reducing and increasing electric, heating, and cooling demands of residential and commercial buildings;
- With respect to dynamic energy utilization for buildings: 4. Quantify the impacts of broad implementation of energy storage such as batteries and/or thermal energy storage on the impact of electric grid requirements; 5. Quantify how dynamic demand response or load management with energy storage can impact energy requirements for buildings/communities; 6. Describe the role of LEED Certification in driving building energy efficiency;
- With respect to energy utilization for industrial processes: 7. Analyze two energy intensive manufacturing processes (chemical or materials) and write review of technologies that impact their energy needs, requirements, and costs over the next two decades; 8. Develop understanding of how changing energy and utility supplies can impact process efficiency and environmental impact on energy intensive manufacturing processes; 9. Articulate the impact of PURPA (Public Utility Regulatory Policies Act), and Energy Policy Acts of 1992, and 2005.
- With respect to advanced energy grids and distributed power: 10. Articulate advances in distributed power and advanced controls and their impact upon grid operation and utility markets in a smart grid framework for the U.S.; 11. Evaluate for one energy-intensive industrial process the energy, economic benefits for combined heat and power or combined cooling, heat, and power; 12. Identify the challenges and risks arises due to cyber-security in a smart grid and articulate awareness of the essential tools used to secure grid infrastructure.

**ENGY550. FUNDAMENTALS OF SOLAR ENERGY ENGINEERING. 3.0 Semester Hrs.**
This course will go over the solar resource and components of solar irradiance; principles of photovoltaic devices; wafer-based and thin film photovoltaic modules; photovoltaic system design; photovoltaic electrical energy production and cost analysis of photovoltaic systems relative to fossil fuel alternatives; integration into conventional energy systems; introduction to concentrated photovoltaic systems, solar water heating, solar ventilation air preheating, and passive solar building design. Case studies include net zero residential and commercial buildings and utility-scale solar plants. The instructor will be Andy Walker. Dr. Walker has 40 years of experience with solar energy research and deployment and has authored several publications including the course textbook. Dr. Walker has been recognized with several awards including Thomas Alva Edison Patent Award for Renewable Energy Optimization software. He has a BS, MS, and PhD in Mechanical Engineering and is a Registered Professional Engineer. Dr. Walker has been teaching courses since 1999 and also serves as Senior Research Fellow at National Renewable Energy Laboratory. Prerequisites: PHGN200 and MATH225.
**Course Learning Outcomes**

- Derive relations based on key concepts of physics (quantum and spectral concepts; boundary layer theory; energy balance; heat exchanger effectiveness) to design and analysis of solar energy systems.
- Derive relations based on key concepts of physics (quantum and spectral concepts; boundary layer theory; energy balance; heat exchanger effectiveness) to design and analysis of solar energy systems.
- Understand the operating principle of key solar energy technologies.
- Understand the function of each component of a solar energy system and how components are assembled into systems.
- Practice handbook and computer methods to estimate solar system energy delivery.
- Understand the life-cycle economics and financing strategies for solar energy systems and practice cost-estimating.
- Understand the financing and contracting process by which solar energy systems are delivered.
- Instill awareness of the effects of a solar energy system on the larger utility system and on the environment.

**ENGY598. SPECIAL TOPICS. 0-6 Semester Hr.**

**ENGY598. SPECIAL TOPICS. 0-6 Semester Hr.**

**ENGY598. SPECIAL TOPICS. 0-6 Semester Hr.**

**ENGY599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**ENGY691. INTRODUCTION TO RESEARCH METHODS IN THE ENERGY SCIENCES. 3.0 Semester Hrs.**
This course introduces graduate students enrolled in the Advanced Energy Systems Program to research opportunities, culture, and expectations in energy science and technology with a particular emphasis on systems and/or policy analysis. Students will work within directorates at NREL with an emphasis on systems modeling, analysis, and/or

integration. This class will engage students in a semester-long research project in energy system analysis and prepare students for best practices with respect to research project and data management, literature reading, report writing, and presentation.

**Course Learning Outcomes**

- With respect to research skills and practices: 1. Learn how to perform a detailed literature review and summary in support of a research project; 2. Develop strong habits for documenting research progress and reporting to other researchers and management on regular basis; 3. Exhibit working knowledge of good practices in data management during research; 4. Demonstrate competency in presenting research in a professional, technical presentation;
- With respect to energy systems analysis: 5. Perform a publication-quality techno-economic or systems analysis to assess energy-relevant technology, innovation, or policy for informing decision-making; 6. Leverage existing models and develop new models to evaluate advanced energy technologies, systems, and services.

**ENGY692. PROJECT FOCUSED RESEARCH IN ENERGY SCIENCE & TECHNOLOGY. 3.0 Semester Hrs.**

(I) This course prepares graduate students enrolled in the Advanced Energy Systems Program in research practices, culture, and expectations in energy science and technology with a particular emphasis on science and engineering related to energy materials, processes, and/or systems. Students will work within directorates at NREL with an emphasis on science and/or technology. This class will engage students in a semester-long research project in energy science and/or technology. Students will also learn and practice journal publication and research poster best practices, research career path planning, and proposal funding strategies. 1 hour lecture; 6 hours lab; 3 semester hours.

**Course Learning Outcomes**

- With respect to journal article and poster preparation: 1. Develop strong skills in literature review and paper preparation; 2. Demonstrate skills with respect to preparing a publication outline and figure list; 3. Write a report that has the structure and quality of a journal publication; 4. Prepare a poster summarizing research motivation and results from semester project;
- With respect to career development and supporting skills: 5. Articulate career paths related to advanced energy systems and identifying skills for preparation 6. Prepare and critique proposal project summaries for energy-related science and technology research; 7. Demonstrate ability to identify funding opportunities and promote research;
- With respect to energy science, technology, and innovation research: 8. Perform a research study on an advance energy science and technology development in line with career and research interest and NREL programs; 9. Demonstrate working knowledge of best laboratory practices with respect to safety, notebook recording, and uncertainty. 10. Be able to motivate the topic of research through techno-economic analysis 11. Be able to define a research hypothesis and develop a parametric test procedure to evaluate it

**ENGY693. AES GRADUATE STUDENT SEMINAR. 0.5 Semester Hrs.**

The Advanced Energy Systems Graduate Student Seminar is a series of presentations provided by graduate students to fellow graduate students, faculty, mentors, and guests. All Ph.D. students are expected to register for this course. The seminar course provides students, faculty, and mentors working in the AES Graduate Program an opportunity to hear updates on current research within the various cohorts and provides a chance for students to get constructive feedback on their presentation. In addition, the course will provide a venue for discussions on various topics related to methods for succeeding in research careers in academia, national labs, and industry, and topics of the day. The course format will be to have two graduate-student presentations with critical feedback, followed by a discussion session on various professional development topics.

**ENGY707. GRADUATE THESIS. 1-15 Semester Hr.**

## Professor and Program Director

Robert Braun, University Distinguished Professor, Mechanical Engineering

## AES Steering Committee

Robert Braun (ME), Director and Chair

Morgan Bazilian (EB)

Tzahi Cath (CEE)

Steven DeCaluwe (ME)

Greg Jackson (ME)

Michael Kaufman (MME)

Monica Kosanovich (AES)

Stephanie Kwon (ChemE)

Salman Mohagheghi (EE)

Alexandra Newman (OR)

Ryan O'Hayre (MME)

Matthew Posewitz (Chem)

Vladan Stevanovic (MME)

Paulo Tabares Velasco (ME)

Jeramy Zimmerman (PHYS)

## NREL AES Steering Committee

Adam Waren, AES Co-Director, NREL

Nancy Haegel

Kate Anderson

Matthew Thornton

## Interdisciplinary Talents

In addition to the steering committee members, the AES program engages the interdisciplinary expertise of colleagues from various departments at Mines and NREL who serve as research mentors, co-instructors, academic advisors and committee members.

# Additive Manufacturing

## Program Description

The Additive Manufacturing program provides graduates and professional students with the practical, interdisciplinary skills to apply cutting-edge

additive manufacturing techniques to a wide range of industries, including aerospace, biomedical, defense, and energy, among others.

This program highlights the core foundations of additive manufacturing: process, design, and materials. Students can choose to from a wide range of electives across a variety of categories including data science and machine learning, operational efficiency of manufacturing operations, and entrepreneurship and technology management. The program focuses on additive manufacturing of structural materials and provides users with the skills they need to apply additive manufacturing in modern manufacturing environments.

## Contact

Craig Brice
Director, Additive Manufacturing
https://additive.mines.edu/ (https://additive.mines.edu/)

**Master of Science in Additive Manufacturing (Non-Thesis) (30 credits)**

The Master of Science in Additive Manufacturing (non-thesis) provides students the opportunity to explore a wide range of manufacturing technologies and methodologies necessary to fabricate engineered products in current and emerging markets.

The core courses in the Additive Manufacturing program give students a foundation in additive manufacturing along with options to explore topics across various fabrication and manufacturing efficiency areas. Students enrolled in the Master of Science in Additive Manufacturing (non-thesis) program will complete 9 credits of core courses listed below along with 21 credits of elective courses from the Additive Manufacturing list. The elective list is broken into focus areas to aid students interested in a specific area of additive manufacturing. Students are not required to select a focus area but can choose electives across the entire list.

| | | |
|---|---|---|
| AMFG501 | ADDITIVE MANUFACTURING | 3.0 |
| AMFG521 | DESIGN FOR ADDITIVE MANUFACTURING | 3.0 |
| AMFG531 | MATERIALS FOR ADDITIVE MANUFACTURING | 3.0 |
| ELECTIVES | Select electives from the Additive Manufacturing list below Up to 6 hours may be replaced with project-based independent study | 21.0 |
| **Total Semester Hrs** | | **30.0** |

## Mines' Combined Undergraduate/Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

## Additive Manufacturing Electives

Note that, while the listed electives are grouped into focus areas, students are not required to select a specific focus area for their degree.

| | | |
|---|---|---|
| **Materials Manufacturing Focus Area** | | |
| MEGN511 | FATIGUE AND FRACTURE | 3.0 |
| MEGN515 | COMPUTATIONAL MECHANICS | 3.0 |
| MTGN531 | THERMODYNAMICS OF METALLURGICAL AND MATERIALS PROCESSING | 3.0 |
| MTGN536 | OPTIMIZATION AND CONTROL OF METALLURGICAL SYSTEMS | 3.0 |
| MTGN557 | SOLIDIFICATION | 3.0 |
| MTGN560 | ANALYSIS OF METALLURGICAL FAILURES | 3.0 |
| MTGN564 | ADVANCED FORGING AND FORMING | 3.0 |
| MTGN565 | MECHANICAL PROPERTIES OF CERAMICS AND COMPOSITES | 3.0 |
| ELECT | Electives As Approved By Advisor | |
| **Design Manufacturing Focus Area** | | |
| AMFG592 | ADDITIVE MANUFACTURING BUILD PREPARATION | 1.0 |
| FEGN525 | ADVANCED FEA THEORY & PRACTICE | 3.0 |
| FEGN526 | STATIC AND DYNAMIC APPLICATIONS IN FEA | 3.0 |
| FEGN527 | NONLINEAR APPLICATIONS IN FEA | 3.0 |
| FEGN528 | FEA FOR ADVANCED DESIGN APPLICATIONS | 3.0 |
| ELECT | Electives As Approved By Advisor | |
| **Manufacturing Controls and Data Science Focus Area** | | |
| AMFG511 | DATA DRIVEN ADVANCED MANUFACTURING | 3.0 |
| CSCI507 | INTRODUCTION TO COMPUTER VISION | 3.0 |
| CSCI534 | ROBOT PLANNING AND MANIPULATION | 3.0 |
| CSCI562 | APPLIED ALGORITHMS AND DATA STRUCTURES | 3.0 |
| CSCI575 | ADVANCED MACHINE LEARNING | 3.0 |
| CSCI587 | CYBER PHYSICAL SYSTEMS SECURITY | 3.0 |
| DSCI/MATH530 | STATISTICAL METHODS I | 3.0 |
| EENG509 | SPARSE SIGNAL PROCESSING | 3.0 |
| EENG515 | MATHEMATICAL METHODS FOR SIGNALS AND SYSTEMS | 3.0 |
| EENG517 | THEORY AND DESIGN OF ADVANCED CONTROL SYSTEMS | 3.0 |
| MATH551 | COMPUTATIONAL LINEAR ALGEBRA | 3.0 |
| MEGN540 | MECHATRONICS | 3.0 |
| MEGN544 | ROBOT MECHANICS: KINEMATICS, DYNAMICS, AND CONTROL | 3.0 |
| MEGN545 | ADVANCED ROBOT CONTROL | 3.0 |
| MEGN587 | NONLINEAR OPTIMIZATION | 3.0 |
| MEGN588 | INTEGER OPTIMIZATION | 3.0 |
| ELECT | Electives As Approved By Advisor | |
| **Manufacturing Optimization and Business Focus Area** | | |
| AMFG522 | LEAN MANUFACTURING | 3.0 |
| AMFG523 | DESIGN AND ANALYSIS OF EXPERIMENTS | 3.0 |
| MEGN579 | OPTIMIZATION MODELS IN MANUFACTURING | 3.0 |
| CEEN501 | LIFE CYCLE ASSESSMENT | 3.0 |
| EBGN559 | SUPPLY CHAIN ANALYTICS | 3.0 |
| EBGN563 | MANAGEMENT OF TECHNOLOGY AND INNOVATION | 3.0 |
| EBGN576 | MANAGING AND MARKETING NEW PRODUCT DEVELOPMENTS | 3.0 |

| | | |
|---|---|---|
| MEGN592 | RISK AND RELIABILITY ENGINEERING ANALYSIS AND DESIGN | 3.0 |

## Graduate Certificate in Additive Manufacturing (12 credits)

The graduate certificate in Additive Manufacturing provides students the knowledge and skills needed to design, fabricate, and implement engineered components made using additive manufacturing techniques.

The graduate certificate in Additive Manufacturing is offered fully online to accommodate working professionals outside the immediate geographic area. These courses are also available as elective courses in the current Advanced Manufacturing Masters (non-thesis) and graduate certificate in Smart Manufacturing.

The core courses in the Additive Manufacturing program explore the process, design, and material aspects of additive manufacturing. Students enrolled in the graduate certificate program will complete the three core courses found below along with an elective course from the Additive Manufacturing list.

| | | |
|---|---|---|
| AMFG501 | ADDITIVE MANUFACTURING | 3.0 |
| AMFG521 | DESIGN FOR ADDITIVE MANUFACTURING | 3.0 |
| AMFG531 | MATERIALS FOR ADDITIVE MANUFACTURING | 3.0 |
| ELECTIVE | Select elective from the Additive Manufacturing list above | 3.0 |

## Courses

**AMFG501. ADDITIVE MANUFACTURING. 3.0 Semester Hrs.**
This course gives students a broad understanding of additive manufacturing (AM) techniques (popularly known as 3d printing) and how these techniques are applied to make engineered products. The course covers the seven standard classifications of AM processes and compares and contrasts each technique alongside legacy fabrication methods such as milling. Students will also get a high-level view of design, material, and pre/post-processing requirements for AM produced parts along with a fundamental understanding of the cost drivers that make AM competitive over legacy fabrication methods. Prerequisites: MEGN200 and MEGN201 or equivalent project classes.
**Course Learning Outcomes**

- Compare the fundamental differences (speed, accuracy, and cost) between additive manufacturing and subtractive manufacturing.
- Articulate the additive manufacturing process #ow from conceptualization to #nal part.
- Describe the key aspects of each of the seven classi#cations of additive manufacturing technology.
- Compare available post processing methods and select the method(s) that will achieve the desired part characteristics.
- Identify the key di#erences between materials made via additive manufacturing and materials made through conventional fabrication methods in terms of properties, performance, and quali#cation approach.
- Perform a detailed engineering economic analysis to determine if additive manufacturing is the appropriate fabrication method for a given part requirement.
- Utilize design for additive strategies to re-design a conventionally manufactured component assembly and build a prototype of the design using an appropriate additive manufacturing technique.

**AMFG511. DATA DRIVEN ADVANCED MANUFACTURING. 3.0 Semester Hrs.**
(I) Although focused on materials manufacturing, this course is intended for all students interested in experimental design and data informatics. It will include both directed assignments to reinforce the concepts and algorithms discussed in class and a term project that will encourage students to apply these concepts to a problem of their choosing. Some programming background would be beneficial but is not necessary; the basics of python and the sklearn machine learning toolkit will be covered in the first weeks of the course. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- 1. Plan and execute design of experiment using, for example Latin Hypercube, Græco-Latin Hypercube, and sequential learning accelerated design of experiment. (Experimental Design.)
- 2. Develop and utilize best practices for high fidelity data collection and curation. (Data Collection and Preprocessing.)
- 3. Extract actionable information from that data through the evaluation and application of appropriate models. (Data Analysis.)
- 4. Effectively communicate to others the impact of these models and how these models guide and optimize a materials manufacturing process. (Data Visualization.)

**AMFG521. DESIGN FOR ADDITIVE MANUFACTURING. 3.0 Semester Hrs.**
(II) Design for Additive Manufacturing (DAM) introduces common considerations that must be addressed to successfully design or re-design parts for additive manufacturing methods. Industry-leading hardware and FEA software will be used to explore all phases of the DAM workflow, including topology optimization, additive process simulation, distortion compensation, and in-service performance. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- 1. Execute a topology optimization, interpret results, and re-parameterize geometry to facilitate downstream shape/design refinement.
- 2. Explain the key factors driving support placement in an AM part.
- 3. Use software tools to plan the tool path for an AM process.
- 4. Set part orientation in an AM process to minimize surface area or volume of support material.
- 5. Simulate the thermal history of a part manufactured using an AM process.
- 6. Simulate post-production heat treatment for an AM process.
- 7. Optimize part orientation in a powder-bed AM process to minimize part distortion or maximize in-service fatigue life.
- 8. Clearly communicate in writing the findings of an AM design verification evaluation.

**AMFG522. LEAN MANUFACTURING. 3.0 Semester Hrs.**
Throughout the course, students will learn to apply skillsets to real world problems, focusing on lean and six-sigma principles and methodologies. The course is taught with a focus on the DMAIC structure of implementation (define, measure, analyze, improve and control) for improving and implementing process efficiencies in industry. The course is split into three general subject areas; 1) lean manufacturing principles, 2) six-sigma and statistical process control (SPC) methodologies and 3) implementation techniques focusing on graphical and numerical representation of processes using R. Students will receive an in-depth overview of lean manufacturing principles and will perform case studies at local industries to implement learned skill-sets. Next, students will step-

through several hands-on activities using real products to investigate six-sigma and perform SPC analysis, identifying shifts in process data and learning how to shift processes into capable processes. Lastly, students will learn about various implementation techniques for industry and will perform an in-depth analysis of the course topics based on the industry tours performed.

**Course Learning Outcomes**

- • Critique real-time manufacturing processes with regards to information flow, product flow and process times.
- • Identify value adding steps in manufacturing processes in order to better understand where waste lies
- • Recognize real-time wastes in manufacturing processes and facilities and reorganize processes using efficiency models and learned skill-sets to reduce defects found throughout the process
- • Implement lean and six-sigma methodologies to eliminate waste and decrease defects from observed and analyzed processes
- • Utilize R and MiniTab software to create control charts
- • Recognize when to use various applied statistical graphical and numerical representation to understand a process
- • Create analytic reports discussing change implementation plans based on real-time data for upper level management to implement for process efficiency
- • Apply learned skillsets to real-time manufacturing processes and facilities

**AMFG523. DESIGN AND ANALYSIS OF EXPERIMENTS. 3.0 Semester Hrs.**

This course introduces effective experimental design and analysis methodologies relevant to all engineering and scientific disciplines to maximize the information learned from every experiment (test case) while minimizing the total number of tests. We will be using state-of-art methods steeped in statistics to effectively set up your experiments, understand what the results are telling you, and clearly communicate the results to peers and leadership. We apply a disciplined systems engineering approach across the four major experimental phases: plan, design, execute, and analyze. This hands-on class will focus on understanding concepts and practical applications while relying less on the statistical theoretical development. Completion of MATH201 is recommended, not required.

**Course Learning Outcomes**

- At the completion of this course, students will: 1) Formulate an analytically defensible test strategy using foundational principles across the Plan-Design-Execute-Analyze phases of experimentation.
- 2) Apply statistically-based methods to understand results and quantify risk from single factor experiments.
- 3) Create and analyze full-factorial test designs with multiple input explanatory variables understanding the critical importance of interactions.
- 4) Construct appropriate test designs to screen many possible input factors to isolate those few variables that drive system behavior.
- 5) Construct response surface test designs that build on screening methods to characterize nonlinear behavior often seen in practical applications.
- 6) Compare alternative experimental designs with statistically-based performance metrics.
- 7) Assess advanced experimental designs that better fit the actual test environment rather than forcing the problem to conform into a common design.

**AMFG531. MATERIALS FOR ADDITIVE MANUFACTURING. 3.0 Semester Hrs.**

(II) This course will cover various structural materials used in additive manufacturing (AM) processes. Focus will be on polymer, ceramic, and metallic compositions. General chemistry of each material will be covered with additional focus on the behavior of these materials when processed using AM. The course will span the entire AM lifecycle from feedstock fabrication to fabrication by AM to post processing and inspection of as-fabricated material. Students will have hands-on exposure to AM processes and will conduct laboratory studies of AM material properties. Additionally, students will conduct a semester-long research project exploring some aspect of AM materials. 3 hours lecture; 3 semester hours.

**Course Learning Outcomes**

- 1. List the polymer, ceramic, and metallic materials most commonly used in AM processes
- 2. Describe the key features necessary in a material (polymer, ceramic, metal) that make it amenable to AM processes
- 3. Describe the differences between AM processed materials and conventionally processed materials
- 4. Describe the manufacturing processes used to create feedstock materials
- 5. List common defects in AM materials and explain how they form and how they can be avoided
- 6. Describe the common post processing methods for various AM materials and explain why they are necessary and/or useful

**AMFG581. OPTIMIZATION MODELS IN MANUFACTURING. 3.0 Semester Hrs.**

This course explores the process of taking known inputs such as costs, supplies and demands, and determining values for unknown quantities (variables) so as to maximize or minimize some goal (objective function) while satisfying a variety of restrictions (constraints). Such problems arise in manufacturing operations as personnel planning, product sequencing, and plant scheduling. We examine a variety of manufacturing settings, e.g., flow shops, job shops, flexible manufacturing shops, and the corresponding appropriate models to optimize operations. The course explores a mix of mathematical modeling, software use and case studies. Prerequisite: Junior standing in an engineering major, or instructor consent.

**Course Learning Outcomes**

- Understand the concepts of optimization as applied in a manufacturing setting. See syllabus.

**AMFG591. ECONOMIC CONSIDERATIONS FOR ADDITIVE MANUFACTURING. 1.0 Semester Hr.**

This course will provide students an opportunity to explore the economic considerations for advanced manufacturing processes, specifically additive manufacturing (AM). So often, these processes are thought of as being quick, easy, and cheap. While this can be true for prototypes and other non-critical parts, the reality is much different when working with engineered parts. An examination of the underlying engineering details for AM processes reveals many elements of cost and time which must be accounted for when evaluating the affordability of AM for any application. Students will learn about recurring and non-recurring costs, the reasons for post-processing steps such as machining, mechanical testing, and

non-destructive inspection, and the impacts of these considerations on cost and manufacturing span-time. Students should expect to come away from this course better equipped to assess the economic viability of AM for engineering applications.

**Course Learning Outcomes**

- Economic Analysis
- Requirement Differentiation
- Process Formulation
- Additive Manufacturing Cost Estimation

**AMFG592. ADDITIVE MANUFACTURING BUILD PREPARATION. 1.0 Semester Hr.**

This course covers practical aspects of additive manufacturing build preparation, which include designing a part, part build orientation, and support structures. It distinguishes these concepts from those of traditional manufacturing methods and addresses how they influence final part outcome in regard to mechanical performance, dimensional accuracy, surface finish, and post processing requirements. Similarities and differences in these concepts are covered as they apply to various additive manufacturing technologies. These concepts are integrated to ultimately provide students with the ability to holistically approach design for additive manufacturing. Prerequisite: AMFG401 or AMFG501.

**Course Learning Outcomes**

- At the completion of this course, students will: 1) Use CAD software to design and export parts to buildable file formats.
- 2) Use CAD software to apply color, design, and texture to part surfaces.
- 3) Apply concepts of additive manufacturing to design a part or assembly.
- 4) Apply concepts of additive manufacturing to determine part build orientation.
- 5) Apply concepts of additive manufacturing to design support structures.
- 6) Integrate concepts of part design, orientation, and support structures to apply a holistic design strategy to additive manufacturing.
- 7) Differentiate additive manufacturing technologies as functions of their design considerations.

**AMFG598. SPECIAL TOPICS IN ADVANCED MANUFACTURING. 1-6 Semester Hr.**

(I, II) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once. Prerequisite: none. Variable credit; 1 to 6 credit hours. Repeatable for credit under different titles.

**AMFG598. SPECIAL TOPICS IN ADVANCED MANUFACTURING. 1-6 Semester Hr.**

**AMFG599. INDEPENDENT STUDY. 1-6 Semester Hr.**

**AMFG599. INDEPENDENT STUDY. 1-6 Semester Hr.**

**AMFG599. INDEPENDENT STUDY. 1-6 Semester Hr.**

**AMFG599. INDEPENDENT STUDY. 1-6 Semester Hr.**

**AMFG599. INDEPENDENT STUDY. 1-6 Semester Hr.**

## Director and Professor of Practice

Craig A. Brice

# Carbon Capture, Utilization, and Storage

## Degrees Offered

- Masters in Carbon Capture, Utilization, and Storage
- Carbon Capture, Utilization, and Storage Certificate

## Program Description

As global interest in carbon capture, utilization, and storage (CCUS) continues to grow, so does the demand for skilled professionals equipped to tackle its unique challenges. The Mines CCUS graduate certificate program addresses this critical need. By integrating world-renowned expertise in earth sciences, engineering, economics and business, this interdisciplinary program enables students to explore the unique challenges related to CCUS, climate change, and the energy transition while gaining the specialized skills needed to advance their careers.

The Masters in Carbon Capture, Utilization, and Storage (course-based) program is designed to give students a foundation in the technical, business, and community engagement aspects of CCUS to help them further their careers in the CCUS space. This non-thesis, online only program is structured to be of use for both those seeking to expand their career or those just getting started.

The CCUS graduate certificate program is designed for professionals looking to enhance their expertise in carbon capture, utilization, and storage. The courses are fully asynchronous, eight weeks long, and offered online, providing flexibility for working professionals. Students need to complete three courses - two required and one elective - to earn the graduate certificate in CCUS. These courses can also be taken to count towards a graduate degree.

Participants in this program can expect to:

- Assess data on climate change, and the effects of greenhouse gases on climate.
- Develop a solid foundation and proficiency in methods employed for the three aspects of carbon capture, utilization, and storage.
- Learn workflow and practices in the industry. Assess efficiency of CCUS practices.
- Develop skills to better communicate with colleagues in other disciplines in the organization.
- Learn and understand fundamental concepts from well-known, experienced faculty in the field.

## Contact

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Program Director: Yilin Fan
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Program Coordinator: Rachel McDonald
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https://ccus.mines.edu
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## Masters in Carbon Capture, Utilization, and Storage

The Masters in Carbon Capture, Utilization, and Storage (course-based) program is designed to give students a foundation in the technical, business, and community engagement aspects of CCUS to help them

further their careers in the CCUS space. This non-thesis, online only program is structured to be of use for both those seeking to expand their career or those just getting started.

## Program

To receive the MS degree, students will need to complete at least 30 units of online coursework, which includes 9 units in core courses, including a 3-unit capstone course, and 21 credits of electives.

### Required Courses

| | | |
|---|---|---|
| CCUS520 | CLIMATE CHANGE AND SUSTAINABILITY | 3.0 |
| EBGN502 | POLITICAL ECONOMY OF THE ENERGY TRANSITION | 3.0 |
| CCUS585 | CARBON CAPTURE, UTILIZATION, AND STORAGE CAPSTONE | 3.0 |
| **Total Semester Hrs** | | **9.0** |

### Elective Courses

Choose 21 credits of coursework from those listed below. Other electives can be used with prior approval from the Program Director and your advisor.

| | | |
|---|---|---|
| CCUS521 | GEOLOGICAL CARBON CAPTURE UTILIZATION AND SEQUESTRATION (CCUS) | 3.0 |
| CCUS522 | NON-GEOLOGIC CARBON CAPTURE AND UTILIZATION | 3.0 |
| CCUS525 | BIOLOGICAL CARBON CAPTURE AND CONVERSION | 3.0 |
| CCUS530 | THE KINETICS OF CARBON DIOXIDE REACTIONS | 3.0 |
| CCUS598 | CLASS VI WELL DESIGN AND PERMITTING | 3.0 |
| EDNS501 | COMMUNITY-CENTERED APPROACHES TO RESILIENCE | 3.0 |
| EDNS502 | MANAGING AND LEADING IN MULTISTAKEHOLDER ENVIRONMENTS | 3.0 |
| GEOL557 | EARTH RESOURCE DATA SCIENCE 1: FUNDAMENTALS | 3.0 |
| GPGN519 | ADVANCED FORMATION EVALUATION | 3.0 |
| GPGN558 | SEISMIC DATA INTERPRETATION AND QUANTITATIVE ANALYSIS | 3.0 |

## Carbon Capture, Utilization, and Storage Certificate

The Mines graduate certificate in Carbon Capture Utilization and Storage (CCUS) is a three-course, 9-credit, online program that provides graduate-level learning opportunities in climate and societal impacts of elevated levels of atmospheric $CO_2$, quantitative assessment methods of $CO_2$ mitigation, as well as economic and policy analysis of a CCUS economy. By bringing salient aspects of CCUS under one umbrella, students gain and develop the knowledge and expertise to make informed decisions on $CO_2$ mitigation strategies, technologies, and can guide company and/or government policy and economic decisions.

The CCUS certificate program provides students with engaging learning experiences to understand and guide science-based discussions around climate change and how to assess it using environmental data and modeling methods, explore $CO_2$ capture and utilization technologies, and assess geologic utilization and sub-surface storage options. The program equips students with scientific knowledge about each CCUS topic and various technical $CO_2$ mitigation solutions and their risks. The program combines the expertise from our world-renowned graduate programs in Earth Sciences, Engineering, and Economics and Business and distills them into a certificate program on CCUS technologies and CCUS economy. This program is designed for professionals and recent graduates who want to acquire new skills for career advancement or get a head start on an advanced graduate degree. Courses in the program focus on real-world and current challenges and progress in CCUS techniques, and CCUS economics. The certificate program requires three 3-credit graduate courses identified below:  two required courses and the option to choose an elective in either geologic or non-geologic CCUS.

| | | |
|---|---|---|
| **Required Courses** | | |
| CCUS520 | CLIMATE CHANGE AND SUSTAINABILITY | 3.0 |
| EBGN598 | POLTIICAL ECONOMY OF THE ENERGY TRANSITION | 3.0 |
| **Elective Course Options** | | |
| Choose one of the courses listed below. | | |
| CCUS521 | GEOLOGICAL CARBON CAPTURE UTILIZATION AND SEQUESTRATION (CCUS) | 3.0 |
| SYGN598C | Non-Geologic CCUS | 3.0 |
| SYGN598C | CARBON REDUCTION: CAPTURE & UTILIZATION | 3.0 |

**Course Modality:**

All courses are virtual and asynchronous - so students can listen to the lectures at convenience. All material is online and recorded for offline review. There are timed discussions and deliverables each week where students interact with their peers and with the instructors. The office hours are at specific times, but specific times to meet outside of those hours are often arranged depending on schedule conflicts or on geographic locations.

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**CCUS520. CLIMATE CHANGE AND SUSTAINABILITY. 3.0 Semester Hrs.**

This eight-week online course is intended to introduce students to effects of atmospheric CO2 on climate, CO2 mitigation and avoidance strategies, and aspects of ESG when considering mitigation strategies. The course will provide students with much needed working knowledge about effects of Greenhouse Gases (GHGs) using data, and models. It provides cause and effects of GHGs as well as potential solutions that are equitable and sustainable.

**Course Learning Outcomes**

- 1) Use professional communication methods; explain in written format to a non-scientific reader (general public or policy maker) the big picture of Climate Change and what is Climate Change
- 2) Use professional communication methods; communicate in written format to a non-scientific reader (general public or policy maker) the big picture of Climate Change considering the role of Carbon in climate change
- 3) Using professional communication methods, explain to a non-scientific reader the big picture of Climate Change considering How can we assess climate change - what's the science (to the level needed to explain to general public) behind understanding the causes, and modeling for predictions

- 4) Explain in written format to a non-scientific reader (general public or policy maker) how scientists and engineers are studying solutions to climate change.
- 5) Analyze and accurately discuss the analysis of data sets related to climate change and CCUS considering data sources, data errors and uncertainties, and selecting accurate and appropriate data
- 6) Balance the atmospheric carbon budget in a proposed CCUS plan; consider CCUS with an ESG perspective
- 7) Discuss, using known scientific and social science perspectives, ethical considerations, societal impacts and issues of Climate Change and CCUS that should be considered as planning CCUS
- 8) Analyze maps of climate vulnerability; discuss climate equity; assess scientific accuracy of climate maps

**CCUS521. GEOLOGICAL CARBON CAPTURE UTILIZATION AND SEQUESTRATION (CCUS). 3.0 Semester Hrs.**
This course will cover sub-surface aspects of sustainable CCUS projects. Specifically, the topics covered will be geology of the subsurface appropriate for CCUS, how to create sustainable projects, the physics of CO2 transport, injection and storage it's their modeling studies, practical aspects of CO2 flooding, monitoring and verification methods including seismic, gravity and electromagnetic methods, and assessing CO2 capacity and migration. Each week of the course is taught by experts in the area from geology to engineering to geophysics and covers essential topics such as Class VI CCUS wells and EPA permitting, sustainable project development, to detailed physics such as CO2 phase and flow in the subsurface.
**Course Learning Outcomes**

**CCUS522. NON-GEOLOGIC CARBON CAPTURE AND UTILIZATION. 3.0 Semester Hrs.**
Global warming due to increase in concentration of greenhouse gases is arguably the biggest societal problem of our generation and it could pose existential threat to hundreds of millions of people all around the world. There is no unique strategy to address the threats of global warming. It is going to take a concerted effort leveraging all possible technologies including renewable energies and carbon sequestration to develop solutions to this problem. This class is a part of the CCUS course which is geared towards exploring the feasibility of carbon removal for minimizing the global warming. This course specifically focuses on technologies for sequestering carbon dioxide from air or point sources and utilization and/or storage of the sequestered carbon Prerequisite: Basic understanding of engineering principles, basic knowledge of impact of greenhouse gases on global warming, ability to read research papers, ability to write reports.
**Course Learning Outcomes**

- Use professional communication methods; explain in written format to a non- scientific reader (general public or policy maker) the big picture of global warming due to increasing concentrations of carbon dioxide
- Use professional communication methods; communicate in written format to a non- scientific reader (general public or policy maker) the big picture of carbon sequestration for addressing global warming
- Using professional communication methods, explain to a non-scientific reader the big picture of carbon sequestration including understanding the broader context of how a multi-prong approach is necessary to address global warming and specifically what technologies are available for carbon sequestration and storage
- Explain in written format to a non-scientific reader (general public or policy maker) how scientists and engineers are developing solutions to climate change by sequestering carbon dioxide directly from air and/or from point sources
- Understand the challenges and limitations of sequestering carbon dioxide directly from air and from point sources including understanding the process broadly by looking at energy utilization and economics of the process
- Assess the potential role of sequestration in balancing the atmospheric carbon budget in a proposed CCUS plan
- Discuss, using known scientific and social science perspectives, ethical considerations, societal impacts and issues of Climate Change and carbon sequestration
- Analyze feasibility of various approaches discussed in this course and compare with systems already in place

**CCUS525. BIOLOGICAL CARBON CAPTURE AND CONVERSION. 3.0 Semester Hrs.**
Plants, bacteria, and algae have evolved over billions of years to efficiently use sunlight to turn carbon dioxide and water into useful chemicals, a potential solution to the very real problem of climate change. How do they do this? How can we take advantage of these processes? And, how can we improve on them to find practical solutions to address climate change? The purpose of this course is to answer these questions by introducing students to bioconversion, nature's ability to convert CO2 into other molecules. In this online, asynchronous course, students will work collaboratively in small teams to discuss current literature on carbon dioxide bioconversion, evaluate the effects of various parameters on bioconversion rates and efficiencies, and design and present case studies on ways to use plants, algae, and bacteria to convert CO2 to useful material. Prerequisite: None Co-requisite: None Prerequisite: Undergraduate introductory biology course (BIOL300 and BIOL301, or equivalent),Undergraduate general chemistry course (CHGN121 and CHGN122, or equivalent).
**Course Learning Outcomes**

- 1) Analyze how plants, algae, and bacteria contribute to the carbon cycle
- 2) Analyze how plants, algae, and bacteria contribute to the carbon cycle
- 3) Analyze how plants, algae, and bacteria contribute to the carbon cycle
- 4) Evaluate the effect various parameters (such as temperature, pH, salinity, light, etc.) have on the ability of bacteria to convert CO2 via photosynthesis
- 5) Recommend an appropriate biological-based method for capturing CO2 and converting it to a biofuel, based on the needs and available resources of a stakeholder
- 6) Demonstrate the ability to productively contribute to a team evaluating biological methods for CO2 capture and conversion
- 7) Develop and deliver a presentation on biological CO2 capture and conversion catalysts to an audience of postgraduate engineers

**CCUS530. THE KINETICS OF CARBON DIOXIDE REACTIONS. 3.0 Semester Hrs.**
Carbon dioxide is an extremely stable molecule that stays in the atmosphere for hundreds of years. What makes it so stable? Why does it take so long to convert to something else? How can we, as scientists and engineers, use chemistry to turn carbon dioxide into other, useful things, like fuels and materials? The purpose of this course is to answer these questions by delving into the thermodynamics of carbon dioxide, the kinetics of CO2 reactions, and how electrochemistry, photochemistry,

and catalysts can overcome these problems. In this online, asynchronous course, students will work collaboratively in small teams to discuss current literature on CO2 conversion reactions, evaluate the pros and cons of electrochemistry and photochemistry for CO2 conversion, and design and present case studies on ways to use electrocatalysts and photocatalysts to convert CO2 to useful materials. Prerequisite: None Co-requisite: None Prerequisite: Undergraduate introductory chemistry (CHGN121 and CHGN122, or equivalent),Differential equations (MATH225 or equivalent).

**Course Learning Outcomes**

- 1. Propose electrochemical experiments, and interpret the resulting data, that would allow you to differentiate between CO2 reaction mechanisms
- 2. Propose photochemical experiments, and interpret the resulting data, that would allow you to differentiate between CO2 reaction mechanisms
- 3. Explain the underlying thermodynamic problems associated with converting CO2 into other carbon-based chemicals.
- 4. Evaluate CO2 conversion catalysts, based on various methods such as selectivity, turnover, activity, and cost
- 5. Evaluate CO2 reaction mechanisms based on experimental data
- 6. Develop and deliver a presentation on CO2 conversion catalysts to an audience of postgraduate engineers
- 7. Demonstrate the ability to productively contribute to a team evaluating CO2 conversion catalysts

**CCUS585. CARBON CAPTURE, UTILIZATION, AND STORAGE CAPSTONE. 3.0 Semester Hrs.**

In this course students will work individually and in groups to complete a project that requires them to integrate the skills and principles they have learned throughout the CCUS program curriculum and apply these skills to real systems. Prerequisites: CCUS520, EBGN502.

**Course Learning Outcomes**

- Assess data on climate change to identify a problem that CCUS can address
- Use critical thinking skills, creativity, and familiarity with current research to develop potential solutions for problems once they have been identified
- Identify and address knowledge gaps
- Engage with stakeholders to identify strengths and weaknesses associated with implementing a proposed CCUS project
- Effectively communicate, with both novices and experts, about scientific, economic, and policy aspects of CCUS
- Demonstrate the ability to productively contribute to a team identifying and proposing a CCUS project

**EBGN598. POLITICAL ECONOMY OF THE ENERGY TRANSITION. 3.0 Semester Hrs.**

This course provides an overview of economics, business, and political topics that are commonly found in the energy transition. Many of the assignments relate back to skills that are needed to interact with economics, business, and policy professionals. The course is designed for students with little, if any, social science or business training. Students will build a basic knowledge of economics, finance, and business issues that are relevant to energy markets and industries.

**SYGN598. CARBON REDUCTION: CAPTURE & UTILIZATION. 3.0 Semester Hrs.**

This course provides an overview of the technologies used for decarbonization with an introduction to the chemistry of the molecule and the reactive CO2 capture technologies, carbon capture and separation technologies, thermodynamics, and practical applications from a CCUS systems development perspective.

## Program Director

Yilin Fan, Petroleum Engineering, Assistant Professor

## Associated Faculty

Ali Tura, Geophysics, Professor

Anuj Chauhan, Chemical and Biological Engineering , Professor

Erik Menke, Chemistry, Associate Teaching Professor

Ian Lange, Economics and Business, Associate Professor

Jennifer Miskimins, Petroleum Engineering, Professor

Manika Prasad, Geophysics, Professor

# Data Science

## Program Description

The Master of Data Science (non-thesis) program is designed to give candidates a foundation in statistics and computer science and also provide knowledge in a particular application domain of science or engineering. The balance between these three elements is a strength of the program and can prepare candidates for data science careers in industry, government, or for further study at the PhD level. Throughout is an emphasis on working in teams, creative problem solving, and professional development.

The Data Science Certificates are designed for college graduates and professionals interested in the emerging field of data science as applied within their individual fields of study or industries.

## Contact

Program Director: Soutir Bandyopadhyay

Program Co-Director: Zibo Wang

Program Coordinator: Rachel McDonald

datascience.mines.edu

## Master of Data Science (Non-Thesis)

The field of Data Science draws on elements of computer science, statistics and interdisciplinary applications to address the unique needs of gaining knowledge and insight through data analysis. This Masters Non-Thesis program is designed to give candidates a foundation in statistics and computer science and also provide knowledge in a particular application domain of science or engineering. The balance between these three elements is a strength of the program and can prepare candidates for Data Science careers in industry, government, or for

further study at the PhD level. Moreover, the coursework will be flexible and tailored to each candidate. For example, the program will allow a candidate to increase his/her skills in data analytics while developing a focused area of application or alternatively allow a candidate with depth in an area of application to gain skills in statistics and computer science.

## Program Requirements

This program will follow a 3 X 3 + 1 design: three modules and a mini-module.

### Modules (each consisting of three 3-credit courses)

**Data Modeling and Statistical Learning**

| | | |
|---|---|---|
| MATH530 | INTRODUCTION TO STATISTICAL METHODS (Online Only) Students who have passed MATH335 should replace MATH530 with any of the following: MATH500, MATH531, MATH532, MATH533, MATH534, MATH535, MATH536, MATH537, MATH538, or MATH551 | 3.0 |
| MATH560 | INTRODUCTION TO KEY STATISTICAL LEARNING METHODS I (Online Only) | 3.0 |
| MATH561 | INTRODUCTION TO KEY STATISTICAL LEARNING METHODS II (Online Only) | 3.0 |

**Machine Learning, Data Processing and Algorithms, and Parallel Computation**

| | | |
|---|---|---|
| DSCI503 | ADVANCED DATA SCIENCE | 3.0 |
| DSCI570 | INTRODUCTION TO MACHINE LEARNING | 3.0 |
| DSCI575 | ADVANCED MACHINE LEARNING | 3.0 |

### Individualized and Domain Specific Coursework

Electives for the third module can be designed by the student but the plan needs to be approved by the program curriculum committee. Although this individualized module can draw on graduate courses from across the university, two specific examples from engineering and geophysics are given below:

**Electrical Engineering**

| | | |
|---|---|---|
| EENG510 | ADVANCED DIGITAL SIGNAL PROCESSING | 3.0 |
| EENG509 | SPARSE SIGNAL PROCESSING | 3.0 |
| EENG511 | CONVEX OPTIMIZATION AND ITS ENGINEERING APPLICATIONS | 3.0 |
| EENG515 | MATHEMATICAL METHODS FOR SIGNALS AND SYSTEMS | 3.0 |
| or EENG519 | ESTIMATION THEORY AND KALMAN FILTERING | |
| **Geophysics** | | |
| GPGN533 | GEOPHYSICAL DATA INTEGRATION & GEOSTATISTICS | 3.0 |
| GPGN570 | APPLICATIONS OF SATELLITE REMOTE SENSING | 3.0 |

### Mini-module (comprised of three 1-credit courses)

**Professional Development**

| | | |
|---|---|---|
| SYGN502 | INTRODUCTION TO RESEARCH ETHICS | 1.0 |
| SYGN5XX | LEADERSHIP AND TEAMWORK | 1.0 |
| LICM501 | PROFESSIONAL ORAL COMMUNICATION | 1.0 |
| EDNS544 | INNOV8X | 3.0 |

## Sample Course Schedule

**First Year**

| **Fall** | | **lec** | **lab** | **sem.hrs** |
|---|---|---|---|---|
| DSCI503 | ADVANCED DATA SCIENCE | | | 3.0 |
| DSCI570 | INTRODUCTION TO MACHINE LEARNING | | | 3.0 |
| MATH530 | INTRODUCTION TO STATISTICAL METHODS | | | 3.0 |
| ELECT | Elective Approved by Program* | | | 3.0 |
| | | | | **12.0** |
| **Spring** | | **lec** | **lab** | **sem.hrs** |
| DSCI575 | ADVANCED MACHINE LEARNING | | | 3.0 |
| MATH560 | INTRODUCTION TO KEY STATISTICAL LEARNING METHODS I | | | 3.0 |
| ELECT | Elective Approved by Program* | | | 3.0 |
| LICM501 | PROFESSIONAL ORAL COMMUNICATION | | | 1.0 |
| | | | | **10.0** |

**Second Year**

| **Fall** | | **lec** | **lab** | **sem.hrs** |
|---|---|---|---|---|
| MATH561 | INTRODUCTION TO KEY STATISTICAL LEARNING METHODS II | | | 3.0 |
| ELECT | Elective Approved by Program* | | | 3.0 |
| SYGN502 | INTRODUCTION TO RESEARCH ETHICS | | | 1.0 |
| SYGN5XX | LEADERSHIP AND TEAMWORK | | | 1.0 |
| | | | | **8.0** |

**Total Semester Hrs: 30.0**

*Electives for the third module can be designed by the student but the plan needs to be approved by the Data Science program curriculum committee. This individualized module can draw on graduate courses from across the university.

## Mines Combined Undergraduate / Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to six credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with "B-" or better, not be substitutes for required coursework, and meet all other University, Department, and Program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

## Master of Data Science (Non-Thesis) Online

The Master of Data Science (Non-Thesis) program is designed to give candidates a foundation in statistics and computer science and also provide knowledge in a particular application domain of science or engineering. The balance between these three elements is a strength of the program and can prepare candidates for Data Science careers in

industry, government, or for further study at the PhD level. Throughout is an emphasis on working in teams, creative problem solving, and professional development.

This non-thesis master's program gives students a foundation in statistics and computer science, while also providing knowledge in a particular application domain of science or engineering. It is pitched a higher level of statistics and computer science than one would encounter in a typical data analytics curriculum.

The balance between these elements is a strength of the program and prepares students for data science careers in industry, government or for further study at the PhD level. The emphasis on some foundational knowledge will prepare students to be more innovative in their approach to data analysis and not rely on simply using software packages in a standard way. Moreover, the three elective courses can be tailored to each student's interests. This program allows students to either increase their skill in data analytics while *developing a focused area of application* or alternatively to allow a student with depth in one area of application to *gain skills in statistics and computer science*.

# Program

This program will follow a 2 X 3 + 1 electives module design: two core modules (18 credit hours) and a third comprised of pre-approved electives (12 credit hours), for a total of 30 credit hours.

## Required Module: Data Modeling and Statistical Learning

| | | |
|---|---|---|
| MATH530 | INTRODUCTION TO STATISTICAL METHODS<br>Students who have passed MATH335 should replace MATH530 with any of the following: MATH500, MATH531, MATH532, MATH533, MATH534, MATH535, MATH536, MATH537, MATH538, or MATH551 | 3.0 |
| MATH560 | INTRODUCTION TO KEY STATISTICAL LEARNING METHODS I | 3.0 |
| MATH561 | INTRODUCTION TO KEY STATISTICAL LEARNING METHODS II | 3.0 |

## REQUIRED Module: Machine Learning, Data Processing and Algorithms, and Parallel Computation

| | | |
|---|---|---|
| DSCI503 | ADVANCED DATA SCIENCE | 3.0 |
| DSCI570 | INTRODUCTION TO MACHINE LEARNING | 3.0 |
| DSCI575 | ADVANCED MACHINE LEARNING | 3.0 |

## Individualized and Domain Specific Coursework

In addition to the required 18 credit hours above, students must take 12 credit hours of electives. 3 credits must pertain to professional development and the remaining are in areas of subject matter or data science methods. Electives can be designed by the student, but the plan needs to be approved by the program curriculum committee in advance of taking the courses. Although this individualized module can draw on graduate courses from across the university that are relevant to the students' career or focused field, a few specific examples to form a foci in electrical engineering and geophysics are given below. Other course options are listed below these two examples. Also, some examples of professional development courses are included in the last section. The list of courses is not comprehensive, but rather gives illustrative examples of appropriate foci and courses. Some electives may not be available in online or in-person modality, check the bulletin or your advisor for updated information.

### ELECTIVES: Electrical Engineering Foci

| | | |
|---|---|---|
| EENG509 | SPARSE SIGNAL PROCESSING | 3.0 |
| EENG510 | ADVANCED DIGITAL SIGNAL PROCESSING | 3.0 |
| EENG515 | MATHEMATICAL METHODS FOR SIGNALS AND SYSTEMS | 3.0 |
| EENG519 | ESTIMATION THEORY AND KALMAN FILTERING | 3.0 |

### ELECTIVES: Geological & Geophysics Foci

| | | |
|---|---|---|
| GPGN533 | GEOPHYSICAL DATA INTEGRATION & GEOSTATISTICS | 3.0 |
| GPGN570 | APPLICATIONS OF SATELLITE REMOTE SENSING | 3.0 |
| GEGN575 | APPLICATIONS OF GEOGRAPHIC INFORMATION SYSTEMS | 3.0 |
| GEGN579 | PYTHON SCRIPTING FOR GEOGRAPHIC INFORMATION SYSTEMS | 3.0 |
| GEOL557 | EARTH RESOURCE DATA SCIENCE 1: FUNDAMENTALS | 3.0 |
| GEOL558 | EARTH RESOURCE DATA SCIENCE 2: APPLICATIONS AND MACHINE-LEARNING | 3.0 |

### ELECTIVES: Other Subject Area Foci

| | | |
|---|---|---|
| EBGN525 | BUSINESS ANALYTICS | 3.0 |
| EBGN559 | SUPPLY CHAIN ANALYTICS | 3.0 |
| EBGN560 | DECISION ANALYTICS | 3.0 |
| EBGN571 | MARKETING ANALYTICS | 3.0 |
| PEGN551 | PETROLEUM DATA ANALYTICS - FUNDAMENTALS | 3.0 |

# Certificate Programs in Data Science

## Program Requirements

There are five Certificates in Data Science. Applicants for each are required to have an undergraduate degree to be admitted into the Certificate programs. Course prerequisites, if any, are noted for each Certificate program.

Students working toward one of the Data Science Certificates are required to successfully complete 12 credits, as detailed below for each Certificate. The courses taken for the Certificates can be used towards a Master's or PhD degree at Mines, however courses used for one Data Science Certificate cannot also be counted toward another Data Science Certificate.

# Graduate Certificate in Data Science - Statistical Learning (12 credits)

The Data Science - Statistical Learning Graduate Certificate is an online or residential program focusing on statistical methods for interpreting complex data sets and quantifying the uncertainty in a data analysis. The Certificate also includes gaining new skills in computer science but is grounded in statistical models for data, also termed statistical learning, rather than algorithmic approaches. Students will develop an essential skill set in statistical methods most commonly used in data science along with the understanding of the methods' strengths and weaknesses.

Moreover, the coursework will cover a broad range of applications making it relevant for varied scientific and engineering domains.

Applicants must have completed the following courses, or their equivalents, with a B- or better: CSCI261 and CSCI262 Data Structures, MATH332 Linear Algebra and MATH334 Introduction to Probability.

| | | |
|---|---|---|
| DSCI503 | ADVANCED DATA SCIENCE | 3.0 |
| DSCI530 | STATISTICAL METHODS I | 3.0 |
| DSCI560 | INTRODUCTION TO KEY STATISTICAL LEARNING METHODS I | 3.0 |
| DSCI561 | INTRODUCTION TO KEY STATISTICAL LEARNING METHODS II | 3.0 |

## Graduate Certificate in Data Science - Earth Resources (12 credits)

The Graduate Certificate in Data Science - Earth Resources is an online program building on the foundational concepts in data science as it pertains to managing surface and subsurface Earth resources and on specific applications (use cases) from the petroleum and minerals industries as well as water resource monitoring and remote sensing of Earth change. The Certificate includes one core introductory Data Science course, two courses specific to Earth resources and one elective.

| | | |
|---|---|---|
| DSCI503 | ADVANCED DATA SCIENCE | 3.0 |
| GEOL557 | EARTH RESOURCE DATA SCIENCE 1: FUNDAMENTALS | 3.0 |
| GEOL558 | EARTH RESOURCE DATA SCIENCE 2: APPLICATIONS AND MACHINE-LEARNING | 3.0 |
| ELECTIVE | (1) ELECTIVE FROM LIST BELOW | 3.0 |

**Graduate Certificate in Data Science - Earth Resources Electives (select ONE (1) from the list below):**

| | | |
|---|---|---|
| **Geospatial Focus:** | | |
| GEGN575 | APPLICATIONS OF GEOGRAPHIC INFORMATION SYSTEMS | 3.0 |
| GEGN579 | PYTHON SCRIPTING FOR GEOGRAPHIC INFORMATION SYSTEMS | 3.0 |
| **Petroleum Focus:** | | |
| GPGN519 | ADVANCED FORMATION EVALUATION | 3.0 |
| GPGN547 | PHYSICS, MECHANICS, AND PETROPHYSICS OF ROCKS | 3.0 |
| GPGN558 | SEISMIC DATA INTERPRETATION AND QUANTITATIVE ANALYSIS | 3.0 |
| GPGN651 | ADVANCED SEISMOLOGY | 3.0 |
| PEGN522 | ADVANCED WELL STIMULATION | 3.0 |
| PEGN551 | PETROLEUM DATA ANALYTICS - FUNDAMENTALS | 3.0 |
| **Mining Focus:** | | |
| MNGN548 | INFORMATION TECHNOLOGIES FOR MINING SYSTEMS | 3.0 |
| **Hydrology Focus:** | | |
| CEEN581 | WATERSHED SYSTEMS MODELING | 3.0 |
| **Additional Options:** | | |
| DSCI/MATH530 | STATISTICAL METHODS I | 3.0 |
| EBGN525 | BUSINESS ANALYTICS | 3.0 |

## Graduate Certificate in Petroleum Data Analytics (12 credits)

The Graduate Certificate in Petroleum Data Analytics is an online program building on the foundational concepts in statistics and focusing on the data foundation of the oil and gas industry, the challenges of Big Data to oilfield operations and on specific applications (use cases) for petroleum analytics. The Certificate includes two core introductory Data Science courses and two course specific to petroleum engineering.

| | | |
|---|---|---|
| DSCI503 | ADVANCED DATA SCIENCE | 3.0 |
| DSCI530 | STATISTICAL METHODS I | 3.0 |
| PEGN551 | PETROLEUM DATA ANALYTICS - FUNDAMENTALS | 3.0 |
| PEGN552 | PETROLEUM DATA ANALYTICS - APPLICATIONS | 3.0 |

## Graduate Certificate in Business Analytics

```
The certificate is an online or residential program. The
 requirements are to complete the core course and two elective
 courses:
```

| | | |
|---|---|---|
| **Core Course** | | |
| EBGN525 | BUSINESS ANALYTICS | 3.0 |
| **Elective Courses** | | |
| EBGN559 | SUPPLY CHAIN ANALYTICS | 3.0 |
| EBGN560 | DECISION ANALYTICS | 3.0 |
| EBGN571 | MARKETING ANALYTICS | 3.0 |

Course substitutions may be approved on a case-by-case basis by the certificate director. Completing the certificate will also position students to apply to either the master of science in engineering and technology management degree or the master of science in data science degree, as the certificate courses can be applied to either degree.

## Graduate Certificate in Data Science - Foundations (12 credits)

The Data Science - Foundations Graduate Certificate is an online or residential program focusing on the foundational concepts in statistics and computer science that support the explosion of new methods for interpreting data in its many forms. The Certificate balances an introduction to data science with teaching basic skills in applying methods in statistics and machine learning to analyze data. Students will gain a perspective on the kinds of problems that can be solved by data intensive methods and will also acquire new analysis skills outside of the certificate. Moreover, the coursework will cover a broad range of applications, making it relevant for varied scientific and engineering domains.

Applicants must have completed the following courses, or their equivalents, with a B- or better: CSCI261 and CSCI262 Data Structures, MATH332 Linear Algebra and MATH334 Introduction to Probability.

| | | |
|---|---|---|
| DSCI503 | ADVANCED DATA SCIENCE | 3.0 |
| DSCI570 | INTRODUCTION TO MACHINE LEARNING | 3.0 |
| MATH530 | INTRODUCTION TO STATISTICAL METHODS | 3.0 |

| | |
|---|---|
| MATH560 | INTRODUCTION TO KEY STATISTICAL LEARNING METHODS I |

## Graduate Certificate in Data Science - Computer Science (12 credits)

The Data Science - Computer Science Graduate Certificate is an online or residential program focusing on data science concepts within computer science (e.g., computational techniques and machine learning) plus prerequisite knowledge (e.g., probability and regression). The aim of this certificate is to help students develop an essential skill set in data analytics, including (1) deriving predictive insights by applying advanced statistics, modeling, and programming skills, (2) acquiring in-depth knowledge of machine learning and computational techniques, and (3) unearthing important questions and intelligence for a range of industries, from product design to finance.

Applicants must have completed the following courses, or their equivalents, with a B- or better: CSCI261 and CSCI262 Data Structures, MATH213 Calculus III and MATH332 Linear Algebra. DSCI530 Statistical Methods I, will serve as the MATH201 Probability and Statistics prerequisite for the two machine learning courses of the certificate (DSCI570 Introduction to Machine Learning and DSCI575 Machine Learning).

| | | |
|---|---|---|
| DSCI503 | ADVANCED DATA SCIENCE | 3.0 |
| MATH530 | INTRODUCTION TO STATISTICAL METHODS | 3.0 |
| DSCI570 | INTRODUCTION TO MACHINE LEARNING | 3.0 |
| DSCI575 | ADVANCED MACHINE LEARNING | 3.0 |

## Courses

**DSCI503. ADVANCED DATA SCIENCE. 3.0 Semester Hrs.**
(I, II) This course will teach students the core skills needed for gathering, cleaning, organizing, analyzing, interpreting, and visualizing data. Students will use the python programming language and related toolkits for data manipulation and the use and application of statistical and machine learning for data analysis. The course will be primarily focused on applications, with an emphasis on working with real (non-synthetic) datasets. Students will propose and design a semester project using a dataset from their domain of interest, leveraging the concepts and skills acquired from this course (e.g., data analysis, ethical considerations, evaluation and synthesis of results, storytelling and visualization). Prerequisite: CSCI200 with a grade of C- or higher or CSCI262 with a grade of C- or higher, MATH201 or MATH334 OR Graduate level standing and at least CSCI128 or equivalent.
**Course Learning Outcomes**

- Conduct data acquisition using a varied set of techniques structured and unstructured datasets; including raw data files, SQL databases, online repositories, and programmatically through web scraping and APIs.
- Apply preprocessing strategies to complex and dynamic datasets using industry-standard toolkits and machine learning algorithms to extract features, reduce dimensionality, remove errors, inconsistencies, and missing values.
- Differentiate between machine learning approaches such as classification, regression, clustering, and neural networks for predictive analytics and pattern recognition.
- Evaluate the predictive power of the different statistical and machine learning methods to solve real-world data science problems.
- Develop storytelling and visualization techniques to effectively communicate (exploratory) or persuade (explanatory) findings to a specific audience.
- Critically asses ethical considerations and challenges related to data collection and analysis.
- Construct a comprehensive data science project from inception to presentation, integrating the various techniques and tools learned throughout the course.

**DSCI530. STATISTICAL METHODS I. 3.0 Semester Hrs.**
Introduction to probability, random variables, and discrete and continuous probability models. Elementary simulation, data summarization and analysis using the R Data Analysis Environment. Confidence intervals and hypothesis testing for means and variances. Chi square tests. Distribution-free techniques and regression analysis. Students are expected to have knowledge of probability covered in MATH334 or an equivalent course. Prerequisite: MATH334 or equivalent.

**DSCI560. INTRODUCTION TO KEY STATISTICAL LEARNING METHODS I. 3.0 Semester Hrs.**
Part one of a two-course series introducing statistical learning methods with a focus on conceptual understanding and practical applications. Methods covered will include Introduction to Statistical Learning, Linear Regression, Classification, Resampling Methods, Basis Expansions, Regularization, Model Assessment and Selection. Prerequisite: DSCI530 or MATH530.

**DSCI561. INTRODUCTION TO KEY STATISTICAL LEARNING METHODS II. 3.0 Semester Hrs.**
Equivalent with MATH561,
Part two of a two course series introducing statistical learning methods with a focus on conceptual understanding and practical applications. Methods covered will include Non-linear Models, Tree-based Methods, Support Vector Machines, Neural Networks, Unsupervised Learning. Prerequisite: DSCI560 or MATH560.

**DSCI570. INTRODUCTION TO MACHINE LEARNING. 3.0 Semester Hrs.**
(I, II) The goal of machine learning is to build computer systems that improve automatically with experience, which has been successfully applied to a variety of application areas, including, for example, gene discovery, financial forecasting, and credit card fraud detection. This introductory course will study both the theoretical properties of machine learning algorithms and their practical applications. Students will have an opportunity to experiment with machine learning techniques and apply them to a selected problem in the context of term projects. Graduate students must complete a more challenging project that utilizes complex machine learning algorithms, requiring a deeper understanding of machine learning approaches and critical thinking. Prerequisite: DSCI503.
**Course Learning Outcomes**

- Apply supervised, unsupervised, reinforcement machine learning models and deep learning models to solve problems in areas such as prediction, recognition and classification.
- Explore and develop with various tools, techniques and libraries in Python for data processing, feature extraction, visualization, validation and evaluation.
- Create data visualization tools, techniques, and libraries in Python to visualize high dimensional or complex data for stakeholders.
- Determine ethical implications through interpretability of big data and results from the application of various machine learning models.

- Design and develop a machine learning product that solves their chosen real-world challenge.
- Create a video presentation that succinctly outlines the problem, solutions, conclusions, and lessons learned regarding product development for the stakeholders.

**DSCI575. ADVANCED MACHINE LEARNING. 3.0 Semester Hrs.**
The goal of machine learning research is to build computer systems that learn from experience and that adapt to their environments. Machine learning systems do not have to be programmed by humans to solve a problem; instead, they essentially program themselves based on examples of how they should behave, or based on trial and error experience trying to solve the problem. This course will focus on the methods that have proven valuable and successful in practical applications. The course will also contrast the various methods, with the aim of explaining the situations in which each is most appropriate. Prerequisite: DSCI570.

**DSCI598. SPECIAL TOPICS. 0-6 Semester Hr.**

**DSCI598. SPECIAL TOPICS. 1-6 Semester Hr.**

**DSCI598. SPECIAL TOPICS. 1-6 Semester Hr.**

**DSCI598. SPECIAL TOPICSE. 1-6 Semester Hr.**

**DSCI598. DATA SCIENCE. 1-6 Semester Hr.**

**DSCI599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**DSCI599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

## Professor

Douglas Nychka, Applied Mathematics & Statistics

## Associate Professors

Dorit Hammerling, Applied Mathematics & Statistics

Soutir Bandyopadhyay, Applied Mathematics and Statistics

## Teaching Professor

Wendy Fisher, Computer Science

## Teaching Assistant Professors

Nathan Lenssen, Applied Mathematics and Statistics

Zibo Wang, Computer Science

## Research Associate Professor

Zane Jobe, Geology and Geological Engineering

# FEA Professional

## Degrees Offered

- Graduate Certificate – FEA Professional

## Program Description

The Graduate Certificate – FEA Professional is a fully online graduate-level certificate program that teaches advanced skills in finite-element analysis for structural applications. The program has been designed to train recent graduates or midcareer professionals with at least a BS in engineering, computer science, or applied engineering physics who are interested in careers and/or opportunities in design, product development, or applied research. The program leverages industry-leading software to empower students with the skills and experience to drive innovation in their chosen field. Our courses help students build a foundation of practical knowledge focused on key fundamentals of applied computational mechanics complemented by the perfect balance of theoretical background. The fundamentals learned here may be applicable across a broad range of industries. Upon completion of the program, graduates will have the skills to: a) earn software-specific endorsements/certifications for industry-leading products such as Abaqus, SolidWorks Simulation, ANSYS, b) drive innovation through the effective application of simulation tools for ideation and design verification, c) leverage simulation to reduce physical testing in new product development (NPD) and reduce time to market, d) exploit parametric simulation, DOE, and optimization to reveal more and better R&D solutions, e) identify CTQ's in your development or applied research projects and quantify impact on all relevant outcome metrics, f) execute, review, and manage simulation strategies for your NPD or applied research pipeline, and g) spec software tools and training for your team.

**Program Director and Associate Professor**

Anthony J. Petrella

## Program Requirements

The Graduate Certificate – FEA Professional requires a set of three core courses (Table 1) and one elective chosen from selected relevant online courses (Table 2). Elective options will continue to expand as the program matures.

The student must complete the following three core courses.

| | | |
|---|---|---|
| FEGN525 | ADVANCED FEA THEORY & PRACTICE | 3.0 |
| FEGN526 | STATIC AND DYNAMIC APPLICATIONS IN FEA | 3.0 |
| FEGN527 | NONLINEAR APPLICATIONS IN FEA | 3.0 |

The student must complete one of the following elective courses (3 semester hrs).

| | | |
|---|---|---|
| FEGN528 | FEA FOR ADVANCED DESIGN APPLICATIONS | 3.0 |
| AMFG521 | DESIGN FOR ADDITIVE MANUFACTURING | 3.0 |

## Transfer Credits

Transfer credits are not currently accepted to satisfy requirements for the Graduate Certificate – FEA Professional.

## Prerequesites

A baccalaureate degree in engineering, computer science, a physical science, or mathematics is required.

## Courses

**FEGN525. ADVANCED FEA THEORY & PRACTICE. 3.0 Semester Hrs.**
This course examines the theory and practice of finite element analysis. Direct methods of deriving the FEA governing equations are addressed as well as more advanced techniques based on virtual work and variational methods. Common 1D, 2D, and 3D element formulations are derived, and key limitations examined. Matlab is used extensively to build intuition for FEA solution methods and students will create their own 2D FEA code by the end of the course. The commercial FEA software Abaqus is introduced with hands-on examples and Matlab solutions are compared to Abaqus for model validation.

**Course Learning Outcomes**

- Define DOF.
- Recall three different approaches for developing governing equations in FEA and list typical applications for each.
- Apply FEA governing equations to solve2D structural analysis by hand using symbolic math in Matlab.
- Explain and execute a mesh convergence study.
- Define the isoparametric element formulation and use shape functions to derive isoparametric elements for 2D and 3D applications.
- Recall numbers and locations of integration points for different element types.
- List and explain limitations of common 2D and 3D elements.

**FEGN526. STATIC AND DYNAMIC APPLICATIONS IN FEA. 3.0 Semester Hrs.**
This course emphasizes proficiency with commercial FEA software for solution of practical static, quasistatic, and dynamic structural problems. Common 1D, 2D, and 3D elements are examined in the context of linear solution techniques. Students will explore efficient methods for model construction and solution with commercial tools (the Abaqus FEA software). Emphasis will also be placed on verification, validation, and reporting standards for effective application of FEA software tools. Online course. Prerequisite: FEGN525.
**Course Learning Outcomes**

- Explain the difference between implicit and explicit solvers for static, quasi-static, and dynamic analyses.
- Compare the pros and cons of solutions obtained using implicit and explicit solvers for static, quasi-static, and dynamic analyses.
- Perform a 1D, 2D, or 3D structural analysis with or without symmetry (axi, cyclic).
- Request desired outputs from commercial FEA software and recall the difference between field and history output data types.
- Setup an FEA analysis to request desired output variables defined spatially and temporally.
- Use commercial FEA software pre-processor to visualize results from an FEA solution.

**FEGN527. NONLINEAR APPLICATIONS IN FEA. 3.0 Semester Hrs.**
This course explores common nonlinearities frequently encountered in structural applications of FEA. Students will gain proficiency in modeling geometric nonlinearity (large strains), boundary nonlinearity due to contact, and material nonlinearity (creep, rate dependence, plasticity, temperature effects, residual stress). The commercial FEA software Abaqus is used for hands-on experience. Online course. Prerequisite: FEGN526.
**Course Learning Outcomes**

- Recall and explain the three most common sources of nonlinearity in an FEA simulation.
- Perform an FEA simulation including large strains and finite rotations.
- Execute an FEA simulation including contact and compare several strategies for modeling contact interactions.
- Develop and apply nonlinear models for hyperelastic, viscoelastic, and elastic-plastic materials.
- Use an FEA simulation to compute residual stresses in a part following plastic deformation.
- Construct a clear report to communicate work performed for an FEA simulation.

**FEGN528. FEA FOR ADVANCED DESIGN APPLICATIONS. 3.0 Semester Hrs.**
In this course students will learn the automation tools and methods necessary for effective application of FEA on advanced design problems. Strategies for parametric analysis, performance optimization, and consideration of statistical uncertainty will be examined using Python scripting and commercial automation software. Online course. Prerequisite: FEGN526.
**Course Learning Outcomes**

- Apply Python scripting to automate parametric analysis of a part or assembly using commercial FEA software.
- Apply Abaqus Isight to automate parametric analysis of a part or assembly using commercial FEA software.
- Use Python scripting or other software tools to automate extraction and post-processing of results from commercial FEA software.
- Apply automation tools to perform optimization and probabilistic analysis using commercial FEA software.
- Construct a clear report to communicate work performed for an FEA simulation.

**FEGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**FEGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**FEGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**FEGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**FEGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

# Geochemistry

## Program Description

The Graduate Program in Geochemistry is an interdisciplinary program with the mission to educate students whose interests lie at the intersection of the geological, chemical, hydrological and environmental sciences. The Geochemistry Program consists of two subprograms, administering two MS and PhD degree tracks, two professional master's (non-thesis) degree programs, and a graduate certificate. The Geochemistry (GC) degree track pertains to the history and evolution of the Earth and its features, including but not limited to the chemical evolution of the crust and mantle, geochemistry of energy and mineral resources, aqueous geochemistry and fluid-rock/ fluid-mineral interactions and chemical mineralogy. The Environmental Biogeochemistry (EBGC) degree track pertains to the coupled chemical and biological processes of Earth's biosphere, and the changes in these processes caused by human activities.

## Contact

Program Director: Jim Ranville

geochemistry.mines.edu

Program Coordinator: Rachel McDonald

# Master of Science and Doctor of Philosophy

## 1. Geochemistry degree track

### Prerequisites

In order to identify any course deficiencies, each entering student will have an entrance interview with their temporary advisor or program director. Credit toward a graduate degree will not be granted for courses taken to fulfill deficiencies.

### Program Requirements

The Master of Science (Geochemistry degree track) requires a minimum of 30 credits including:

| | |
|---|---|
| Course Work | 18.0 |
| Research Credits | 6.0 |
| Choice or Research or Coursework | 6.0 |
| **Total Semester Hrs** | **30.0** |

**Table 1**

| | | |
|---|---|---|
| **To ensure breadth of background, the course of study for the Master of Science (Geochemistry degree track) must include:** | | |
| CHGC503 | INTRODUCTION TO GEOCHEMISTRY | 3.0 |
| CHGC504 | METHODS IN GEOCHEMISTRY | 3.0 |
| **Master of Science (Geochemistry) students select at least 12 credits of the following:** | | |
| CHGC509 | INTRODUCTION TO AQUEOUS GEOCHEMISTRY | 3.0 |
| CHGC514 | GEOCHEMISTRY THERMODYNAMICS AND KINETICS | 3.0 |
| CEEN550 | PRINCIPLES OF ENVIRONMENTAL CHEMISTRY | 3.0 |
| GEGN586 | NUMERICAL MODELING OF GEOCHEMICAL SYSTEMS | 3.0 |
| GEGN587 | HYDROCHEMICAL AND TRANSPORT PROCESSES | 3.0 |
| GEGX571 | GEOCHEMICAL EXPLORATION | 3.0 |
| GEOL513 | HYDROTHERMAL GEOCHEMISTRY | 3.0 |
| GEOL523 | REFLECTED LIGHT AND ELECTRON MICROSCOPY * | 2.0 |
| GEOL540 | ISOTOPE GEOCHEMISTRY AND GEOCHRONOLOGY | 3.0 |
| **Approved Elective Options** | | |
| GEGN501 | MINERAL DEPOSITS | 4.0 |
| GEOL518 | MINERAL EXPLORATION | 3.0 |
| GEOL535 | LITHO ORE FORMING PROCESSES | 1.0 |
| Other electives possible with permission of your advisor. | | |

* Students can add one additional credit of independent study (GEOL599) for XRF methods which is taken concurrently with GEOL523.

Master of Science (Geochemistry degree track) students must also complete an appropriate thesis, based upon original research they have conducted. A thesis proposal and course of study must be approved by the student's thesis committee before the student begins substantial work on the thesis research.

The requirements for the Doctor of Philosophy (Geochemistry degree track) program will be established individually by a student's thesis committee, but must meet the minimum requirements presented below. The Doctor of Philosophy (Geochemistry degree track) program will require a minimum of 72 credits beyond the bachelor's degree. A total of 18 course credits beyond the bachelor's degree are required, with at least 9 credits being completed at Mines. A minimum of 12 research credits are required.

Students who enter the PhD program with a thesis-based master's degree may transfer up to 36 credits in recognition of the coursework and research completed for that degree. At the discretion of the student's thesis committee, up to 24 credits of previous graduate-level coursework (at Mines or elsewhere) can be applied toward the course requirement of the Doctor of Philosophy (Geochemistry degree track) program.

| | | |
|---|---|---|
| **Doctor of Philosophy (Geochemistry degree track) students must take:** | | |
| CHGC503 | INTRODUCTION TO GEOCHEMISTRY | 3.0 |
| CHGC504 | METHODS IN GEOCHEMISTRY | 3.0 |
| **Students must also select at least 12 credits of the courses listed in Table 1.** | | |

* Students can add one additional credit of independent study (GEOL599) for XRF methods which is taken concurrently with GEOL523.

Doctor of Philosophy (Geochemistry degree track) students must also complete an appropriate thesis-based upon original research they have conducted. A thesis proposal and course of study must be approved by the student's thesis committee before the student begins substantial work on the thesis research.

Master of Science (Geochemistry degree track) will be expected to give one public seminar on their research and Doctor of Philosophy (Geochemistry degree track) students are required to give at least one public seminar in addition to their thesis defense presentation.

## 2. Environmental Biogeochemistry (EBGC) Degree track

### Prerequisites

A candidate for an MS or PhD in the EBGC degree track should have an undergraduate science or engineering degree with coursework including multivariable calculus, two semesters each of physics and chemistry, and one semester each of biology and earth science. Applicants who do not fulfill these requirements may still be admitted but will need to undergo an entrance interview to establish deficiency requirements. Credit toward a graduate degree will not be given for undergraduate courses taken to fulfill deficiencies.

### Program Requirements

Required Curriculum: A thesis proposal and thesis are required for all MS and PhD degrees in the EBGC degree track. MS thesis advisors (or at least one co-advisor) must be members of the EBGC subprogram. PhD thesis committees must have a total of at least four members. PhD advisors (or at least one of two co-advisors) and one additional committee member must be members of the EBGC subprogram. MS students will be expected to give one public seminar on their research; PhD students are required to give at least one in addition to their thesis defense presentation.

**In addition, both MS and PhD students in the EBGC degree track must complete the following coursework:**

| | | |
|---|---|---|
| **1. Two Required Classes:** | | |
| CHGC503 | INTRODUCTION TO GEOCHEMISTRY | 3.0 |
| CHGC504 | METHODS IN GEOCHEMISTRY | 3.0 |
| **2. One Chemistry-Focused Class, chosen from the following list:** | | |
| CHGC505 | INTRODUCTION TO ENVIRONMENTAL CHEMISTRY | 3.0 |
| CHGC509 | INTRODUCTION TO AQUEOUS GEOCHEMISTRY | 3.0 |
| CEEN550 | PRINCIPLES OF ENVIRONMENTAL CHEMISTRY | 3.0 |
| CEEN551 | ENVIRONMENTAL ORGANIC CHEMISTRY | 3.0 |
| **3. One Biology-Focused Class, chosen from the following list:** | | |
| CEEN560 | MOLECULAR MICROBIAL ECOLOGY AND THE ENVIRONMENT | 3.0 |
| CEEN562 | ENVIRONMENTAL GEOMICROBIOLOGY | 3.0 |
| **4. One Earth Science-Focused class, chosen from the following list:** | | |
| GEGN586 | NUMERICAL MODELING OF GEOCHEMICAL SYSTEMS | 3.0 |
| GEGN532 | GEOLOGICAL DATA ANALYSIS | 3.0 |
| GEGX571 | GEOCHEMICAL EXPLORATION | 3.0 |
| GEOL540 | ISOTOPE GEOCHEMISTRY AND GEOCHRONOLOGY | 3.0 |
| **5. At least One elective approved by your advisor.** | | |

| | |
|---|---|
| **Total Credits Required for MS:** | **30.0** |
| **Total Credits Required for PhD:** | **72.0** |

The student's thesis committee may specify additional course requirements and makes final decisions regarding transfer credits.

Students who enter the PhD program with a thesis-based master's degree may transfer up to 36 credits in recognition of the coursework and research completed for that degree. At the discretion of the student's thesis committee, up to 24 credits of previous graduate-level coursework (at Mines or elsewhere) can be applied toward the course requirement of the Doctor of Philosophy (Geochemistry degree track) program.

A total of 18 course credits are required with at least 9 credits being completed at Mines.

### Comprehensive Examination

Doctor of Philosophy (Geochemistry) students in both degree tracks must take a comprehensive examination. It is expected that this exam will be completed within three years of matriculation or after the bulk of coursework is finished, whichever occurs earlier. This examination will be administered by the student's thesis committee and will consist of an oral and a written examination, administered in a format to be determined by the thesis committee. Two negative votes in the thesis committee constitute failure of the examination.

In case of failure of the comprehensive examination, a re-examination may be given upon the recommendation of the thesis committee and approval of the Dean of Graduate Studies. Only one re-examination may be given.

### Mines' Combined Undergraduate/Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

## Graduate Certificate of Analytical Geochemistry

This program offers an opportunity for working professionals to complete graduate level coursework leading to a Graduate Certificate in a short time. The program focuses on providing instruction in a.) the fundamentals of geochemical analysis, which give students the flexibility to respond to changing opportunities in earth and environmental science, and b.) the mechanics of common techniques (sample collection and preparation, XRF, SEM, and ICP), which prepare students for immediate entry into the jobs market. The Certificate program is comprised of 9.0 credits of coursework. Please note that courses cannot be double counted to fulfill the requirements of other Certificates.

**Students are required to take at least 6.0 credits out of the following core courses:**

| | | |
|---|---|---|
| **Core Courses:** | | |
| CHGC504 | METHODS IN GEOCHEMISTRY | 3.0 |
| GEGN532 | GEOLOGICAL DATA ANALYSIS | 3.0 |
| GEOL523 | REFLECTED LIGHT AND ELECTRON MICROSCOPY * | 2.0 |
| GEOL540 | ISOTOPE GEOCHEMISTRY AND GEOCHRONOLOGY | 3.0 |

**Students can choose up to 3.0 credits out of the following elective courses:**

| | | |
|---|---|---|
| **Electives:** | | |
| CHGC503 | INTRODUCTION TO GEOCHEMISTRY | 3.0 |
| CEEN560 | MOLECULAR MICROBIAL ECOLOGY AND THE ENVIRONMENT | 3.0 |
| CEEN562 | ENVIRONMENTAL GEOMICROBIOLOGY | 3.0 |
| CHGN583 | PRINCIPLES AND APPLICATIONS OF SURFACE ANALYSIS TECHNIQUES | 3.0 |
| GEGN586 | NUMERICAL MODELING OF GEOCHEMICAL SYSTEMS | 3.0 |
| GEGN587 | HYDROCHEMICAL AND TRANSPORT PROCESSES | 3.0 |
| GEGX571 | GEOCHEMICAL EXPLORATION | 3.0 |
| GEOL513 | HYDROTHERMAL GEOCHEMISTRY | 3.0 |
| GEOL628 | ADVANCED IGNEOUS PETROLOGY | 3.0 |
| MTGN605 | ADVANCED TRANSMISSION ELECTRON MICROSCOPY | 2.0 |
| PHGN504 | RADIATION DETECTION AND MEASUREMENT | 3.0 |

* Students can add one additional credit of independent study (GEOL599) for XRF methods which is taken concurrently with GEOL523.

## Professional Masters' Degree in Analytical Geochemistry

This program is designed for both full time students and working professionals who want to increase their knowledge and skills, while gaining a thorough up-date of advances across the spectrum of geochemical analysis.

A minimum of 30 credits are required for the PM degree. Students working towards a PM in Analytical Geochemistry are required to take at least 9.0 credits from courses in the Certificate in Analytical Geochemistry core and 3.0 credits from the electives. Up to 6 credits of the additional electives can include an independent study project (CHGC 598) at Mines, federal agencies, or industry, and is highly encouraged.

The Certificate in Analytical Geochemistry can be combined with the Certificate in Exploration Methods to be used towards the Professional Masters in Analytical Geochemistry (Non-thesis), which will allow part-time students to stack their education. When stacking the Certificates, the additional 6 credits required to complete the PM can include an independent study project (CHGC 599) at Mines, federal agencies, or industry, and is highly encouraged. Independent study projects that connect students with local entities will be a priority and will establish a network of future employers for the students and collaborations for CSM.

## Professional Master's Degree in Environmental Geochemistry

The Professional Master's in Environmental Geochemistry program is intended to provide:

1. an opportunity for Mines undergraduates to obtain, as part of a fifth year of study, a Master's in addition to the Bachelor's degree; and
2. additional education for working professionals in the area of geochemistry as it applies to problems relating to the environment.

This is a non-thesis Master's degree program administered by the Environmental Biogeochemistry subprogram of the Geochemistry program, and may be completed as part of a Combined degree program by individuals already matriculated as undergraduate students at Mines, or by individuals already holding undergraduate or advanced degrees and who are interested in a graduate program that does not have the traditional research requirement. The program consists primarily of coursework in geochemistry and allied fields with an emphasis on environmental applications. No research is required though the program does allow for independent study, professional development, internship, and cooperative experience.

**A 9 Credit Core Program Consists of:**

| | | |
|---|---|---|
| CHGC503 | INTRODUCTION TO GEOCHEMISTRY | 3.0 |
| CHGC509 | INTRODUCTION TO AQUEOUS GEOCHEMISTRY | 3.0 |
| or CEEN550 | PRINCIPLES OF ENVIRONMENTAL CHEMISTRY | |
| GEGN566 | GROUNDWATER ENGINEERING | 3.0 |
| **Total Semester Hrs** | | **9.0** |

In addition, 15 credits must be selected from the list below, representing the following core areas: geochemical methods, geographic information system, geological data analysis, groundwater engineering or modeling, hydrothermal geochemistry, isotope geochemistry, physical chemistry, microbiology, mineralogy, organic geochemistry, and thermodynamics.

| | | |
|---|---|---|
| CHGC504 | METHODS IN GEOCHEMISTRY | 3.0 |
| CEEN560 | MOLECULAR MICROBIAL ECOLOGY AND THE ENVIRONMENT | 3.0 |
| CEEN562 | ENVIRONMENTAL GEOMICROBIOLOGY | 3.0 |
| CHGC555 | ENVIRONMENTAL ORGANIC CHEMISTRY | 3.0 |
| CHGN503 | ADV PHYSICAL CHEMISTRY I | 3.0 |
| GEGN532 | GEOLOGICAL DATA ANALYSIS | 3.0 |
| GEGN575 | APPLICATIONS OF GEOGRAPHIC INFORMATION SYSTEMS | 3.0 |
| GEGN581 | ANALYTICAL HYDROLOGY | 3.0 |
| GEGN583 | MATHEMATICAL MODELING OF GROUNDWATER SYSTEMS | 3.0 |
| GEGN586 | NUMERICAL MODELING OF GEOCHEMICAL SYSTEMS | 3.0 |
| GEGX571 | GEOCHEMICAL EXPLORATION | 3.0 |
| GEOL540 | ISOTOPE GEOCHEMISTRY AND GEOCHRONOLOGY | 3.0 |

An additional 6 credits of free electives may be selected to complete the 30 credit requirement. Free electives may be selected from the course offerings of the Department of Geology and Geological Engineering, the Department of Chemistry, or the Department of Civil and Environmental Engineering, and may also be independent study credits taken to fulfill a research cooperative, or other professional development experience. A course program will be designed in advanced through consultation between the student and an advisor from the Geochemistry Committee of the Whole

## Courses

**CHGC503. INTRODUCTION TO GEOCHEMISTRY. 3.0 Semester Hrs.**
(I) A comprehensive introduction to the basic concepts and principles of geochemistry, coupled with a thorough overview of the related principles of thermodynamics. Topics covered include: nucleosynthesis, origin of earth and solar system, chemical bonding, mineral chemistry, elemental distributions and geochemical cycles, chemical equilibrium and kinetics, isotope systematics, and organic and biogeochemistry. Prerequisite: Introductory chemistry, mineralogy and petrology. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Demonstrate grasp on core concepts of Geochemistry

**CHGC504. METHODS IN GEOCHEMISTRY. 3.0 Semester Hrs.**
(II) Field sampling of natural earth materials including rocks, soils, sediments, and waters. Preparation of naturally heterogeneous materials, digestions, and partial chemical extractions. Principles of instrumental analysis including trace elemental analysis by ICP-atomic spectroscopy, isotope analysis by ICP-MS, EM/X-ray methods, and chromatography. Quality assurance and quality control. Interpretation and assessment of geochemical data using statistical methods. Course format is hands-on, project oriented. Prerequisite: Graduate standing in geochemistry or environmental science and engineering. 2 hours lecture, 3 hours lab; 3 semester hours.
**Course Learning Outcomes**

- Graduates will contribute to the advancement of their chosen fields through interpretation and assessment of statistical methods of geochemical data.

**CHGC505. INTRODUCTION TO ENVIRONMENTAL CHEMISTRY. 3.0 Semester Hrs.**
Equivalent with CHGN403,
(II) Processes by which natural and anthropogenic chemicals interact, react, and are transformed and redistributed in various environmental compartments. Air, soil, and aqueous (fresh and saline surface and groundwaters) environments are covered, along with specialized environments such as waste treatment facilities and the upper atmosphere. Meets with CHGN403. CHGN403 and CHGC505 may not both be taken for credit.

**CHGC506. WATER ANALYSIS LABORATORY. 2.0 Semester Hrs.**
Instrumental analysis of water samples using spectroscopy and chromatography. Methods for field collection of water samples and field measurements. The development of laboratory skills for the use of ICP-AES, HPLC, ion chromatography, and GC. Laboratory techniques focus on standard methods for the measurement of inorganic and organic constituents in water samples. Methods of data analysis are also presented. Prerequisite: Introductory chemistry, graduate standing. 3 hour laboratory, 1 hour lecture, 2 semester hours.

**CHGC508. ANALYTICAL GEOCHEMISTRY. 3.0 Semester Hrs.**
Sample preparation and instrumental analysis of geochemical materials using ICP-AES, ICP-MS, LA-ICP-MS, XRF and XRD are key activities in the field of earth resources and environmental monitoring. Course format is hands-on, project oriented. Laboratory techniques focus on industry-standard methods for the measurement of inorganic constituents, QA/QC, instrument trouble-shooting, and practical exercises with field collected samples. Methods of data interpretation are also key aspects of the course.
**Course Learning Outcomes**

- At the completion of the course students will:

**CHGC509. INTRODUCTION TO AQUEOUS GEOCHEMISTRY. 3.0 Semester Hrs.**
Analytical, graphical and interpretive methods applied to aqueous systems. Thermodynamic properties of water and aqueous solutions. Calculations and graphical expression of acid-base, redox and solution-mineral equilibria. Effect of temperature and kinetics on natural aqueous systems. Adsorption and ion exchange equilibria between clays and oxide phases. Behavior of trace elements and complexation in aqueous systems. Application of organic geochemistry to natural aqueous systems. Light stable and unstable isotopic studies applied to aqueous systems. Prerequisite: CHGN209 or CBEN210.

**CHGC511. GEOCHEMISTRY OF IGNEOUS ROCKS. 3.0 Semester Hrs.**
A survey of the geochemical characteristics of the various types of igneous rock suites. Application of major element, trace element, and isotope geochemistry to problems of their origin and modification. Prerequisite: Undergraduate mineralogy and petrology. 3 hours lecture; 3 semester hours. Offered alternate years.

**CHGC514. GEOCHEMISTRY THERMODYNAMICS AND KINETICS. 3.0 Semester Hrs.**
(II) Fundamental principles of classical thermodynamics and kinetics with specific application to the earth sciences. Volume-temperature – pressure relationships for solids, liquids, gases and solutions. Energy and the First Law, Entropy and the Second and Third Laws. Gibbs Free Energy, chemical equilibria and the equilibrium constant. Solutions and activity-composition relationships for solids, fluids and gases. Phase equilibria and the graphical representation of equilibira. Application of the fundamentals of kinetics to geochemical examples. Prerequisite: Introductory chemistry, introductory thermodynamics, mineralogy and petrology. 3 hours lecture, 3 semester hours. Offered in alternate years.

**CHGC527. ORGANIC GEOCHEMISTRY OF FOSSIL FUELS AND ORE DEPOSITS. 3.0 Semester Hrs.**
A study of organic carbonaceous materials in relation to the genesis and modification of fossil fuel and ore deposits. The biological origin of the organic matter will be discussed with emphasis on contributions of microorganisms to the nature of these deposits. Biochemical and thermal changes which convert the organic compounds into petroleum, oil shale, tar sand, coal and other carbonaceous matter will be studied. Principal analytical techniques used for the characterization of organic matter in the geosphere and for evaluation of oil and gas source potential will be discussed. Laboratory exercises will emphasize source rock evaluation, and oil-source rock and oil-oil correlation methods. Prerequisite: CHGN221, GEGN438. 2 hours lecture; 3 hours lab; 3 semester hours. Offered alternate years.

**CHGC555. ENVIRONMENTAL ORGANIC CHEMISTRY. 3.0 Semester Hrs.**
A study of the chemical and physical interactions which determine the fate, transport and interactions of organic chemicals in aquatic systems, with emphasis on chemical transformations of anthropogenic organic contaminants. Offered in alternate years. 3 hours lecture; 3 semester hours.

**CHGC563. ENVIRONMENTAL MICROBIOLOGY. 2.0 Semester Hrs.**
An introduction to the microorganisms of major geochemical importance, as well as those of primary importance in water pollution and waste treatment. Microbes and sedimentation, microbial leaching of metals from ores, acid mine water pollution, and the microbial ecology of marine and freshwater habitats are covered. Prerequisite: none. 1 hour lecture, 3 hours lab; 2 semester hours. Offered alternate years.

**CHGC564. BIOGEOCHEMISTRY AND GEOMICROBIOLOGY. 3.0 Semester Hrs.**
Designed to give the student an understanding of the role of living things, particularly microorganisms, in the shaping of the earth. Among the subjects will be the aspects of living processes, chemical composition and characteristics of biological material, origin of life, role of microorganisms in weathering of rocks and the early diagenesis of sediments, and the origin of petroleum, oil shale, and coal. Prerequisite: none. 3 hours lecture; 3 semester hours.

**CHGC598. SPECIAL TOPICS. 1-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**CHGC599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**CHGC599. INDEPENDENT STUDY. 1-6 Semester Hr.**

**CHGC599. INDEPENDENT STUDY. 1-6 Semester Hr.**

**CHGC698. SPECIAL TOPICS. 1-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only

once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**CHGC699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**CHGC699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

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**CHGC699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**CHGC707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 0.5-15 Semester Hr.**

## Professors

Alexis Navarre-Sitchler, Geology and Geological Engineering

Bettina M. Voelker, Chemistry

Christopher P. Higgins, Civil and Environmental Engineering

James F. Ranville, Chemistry

John McCray, Civil and Environmental Engineering

John R. Spear, Civil and Environmental Engineering

Jonathan Sharp, Civil and Environmental Engineering

Linda A. Figueroa, Civil and Environmental Engineering

Thomas Monecke, Geology and Geological Engineering

Zhaoshan Chang, Geology and Geological Engineering

## Associate Professors

Mathias Burisch, Geology and Geological Engineering

Yvette Kuiper, Geology and Geological Engineering

## Assistant Professor

Ryan Venturelli, Geology and Geological Engineering

## Affiliate Faculty

Katharina Pfaff, Geology and Geological Engineering, Research Associate Professor

## Emeriti Professor

John B. Curtis, Geology and Geological Engineering

Wendy J. Harrison, Geology and Geological Engineering

Donald L. Macalady, Chemistry

Patrick MacCarthy, Chemistry

Samuel B. Romberger, Geology and Geological Engineering

Richard F. Wendlandt, Geology and Geological Engineering

Thomas R. Wildeman, Chemistry

## Emeriti Associate Professor

L. Graham Closs, Geology and Geological Engineering

E. Craig Simmons, Chemistry

# GIS & GeoInformatics

## Program Description

The interdisciplinary online program in Geographic Information Systems and GeoInformatics (GIS & GeoInformatics) focuses on the applications of geospatial technology. It provides hands-on geospatial training, multi-criteria decision-making, advanced applications, and quantitative analysis in GIS and Remote Sensing (RS). This program aligns directly with the Colorado School of Mines' strengths in Earth, Energy, and Environment. Our programs enhance students' quantitative geospatial analytical skills, position them ahead of the technology curve, and empower professionals to advance their careers.

## Student Learning Outcomes

Students are expected to know and be able to do the following by the time of graduation.

- Master the fundamental concepts of GIS and the skills necessary for conducting geospatial analyses using GIS and/or RS.
- Master the essential principles of optical remote sensing and apply them in image processing.
- Learn and apply the key concepts and principles of Synthetic Aperture Radar (SAR) and Interferometric SAR (InSAR) in InSAR processing.
- Conduct digital elevation model (DEM) acquisition and preparation, creating new map products on a GIS platform to detect spatial and temporal variations of phenomena, such as geomorphic features, landslides, flooding, or forest fires.
- Identify topographic features through the superimposed Digital Elevation Model (DEM) and DEM-derived map products.
- Develop custom Python-based geoprocessing tools and enhance the existing capabilities of GIS applications through Python scripting.
- Automate geoprocessing tasks and#complex spatial#workflows via Python scripting.
- Design and conduct GIS-based projects integrating various datasets, geospatial knowledge, and analytical skills.

## Contact

Program Director: Wendy Zhou

Program Coordinator: Rachel McDonald

## Certificate and Degree Requirements

We offer a graduate certificate and a non-thesis Master of Science degree. The courses taken for the certificate degree can be used towards the Master’s degree.  These programs are available as an online program.

## The Master of Science (Non-Thesis) Program in GIS & GeoInformatics

The Master of Science (Non-Thesis) Program outlined below may be completed by individuals already holding an undergraduate or advanced degree or as a combined degree program by individuals already matriculated as undergraduate students at Colorado School of Mines. Courses taken while working on any of the four GIS & GeoInformatics graduate certificates can be applied to this Master of Science program. The program is comprised of a total of 30 credit hours.

| | | |
|---|---|---|
| All Master of Science (Non-Thesis) program will include the following core requirements: | | |
| GEGN575 | APPLICATIONS OF GEOGRAPHIC INFORMATION SYSTEMS | 3.0 |
| GEGN590 | GIS-BASED REAL WORLD LEARNING PROJECT I - FUNDAMENTALS | 3.0 |
| GEGN592 | GIS-BASED REAL WORLD LEARNING PROJECT II - ADVANCED APPLICATIONS | 3.0 |
| And, seven of the following courses: | | |
| GEGN542 | ADVANCED DIGITAL TERRAIN ANALYSIS | 3.0 |
| GEGN579 | PYTHON SCRIPTING FOR GEOGRAPHIC INFORMATION SYSTEMS | 3.0 |
| GEGN580 | APPLIED REMOTE SENSING FOR GEOENGINEERING AND GEOSCIENCES | 3.0 |
| GEGN588 | ADVANCED PLANETARY GEOGRAPHIC INFORMATION SYSTEMS | 3.0 |
| GEOL557 | EARTH RESOURCE DATA SCIENCE 1: FUNDAMENTALS | 3.0 |
| GEOL558 | EARTH RESOURCE DATA SCIENCE 2: APPLICATIONS AND MACHINE-LEARNING | 3.0 |
| MNGN502 | GEOSPATIAL BIG DATA ANALYTICS | 3.0 |
| DSCI503 | ADVANCED DATA SCIENCE | 3.0 |
| DSCI530 | STATISTICAL METHODS I | 3.0 |
| CEEN501 | LIFE CYCLE ASSESSMENT | 3.0 |
| Students attending on campus also may select from semester based, in person courses GEGN532, GEGN568, CEEN581. | | |

## Mines Combined Undergraduate / Graduate Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to six credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with "B-" or better, not be substitutes for required coursework, and meet all other University, Department, and Program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

**The Graduate Certificate Program in GIS & GeoInformatics** outlined below may be completed by individuals already holding an undergraduate or advanced degree or as a combined degree program by individuals already matriculated as graduate students at Colorado School of Mines. The graduate certificate is comprised of:

| | |
|---|---|
| Course Work | 12.0 |
| **Total Semester Hrs** | **12.0** |

## Graduate Certificate of GIS & GeoInformatics:

Students working towards a Graduate Certificate of GIS & GeoInformatics are required to take any four of the following courses:

| | | |
|---|---|---|
| One Required Course: | | |
| GEGN575 | APPLICATIONS OF GEOGRAPHIC INFORMATION SYSTEMS | 3.0 |
| And, any three of the following courses: | | |
| GEGN542 | ADVANCED DIGITAL TERRAIN ANALYSIS | 3.0 |
| GEGN579 | PYTHON SCRIPTING FOR GEOGRAPHIC INFORMATION SYSTEMS | 3.0 |
| GEGN580 | APPLIED REMOTE SENSING FOR GEOENGINEERING AND GEOSCIENCES | 3.0 |
| GEGN588 | ADVANCED PLANETARY GEOGRAPHIC INFORMATION SYSTEMS | 3.0 |
| GEOL557 | EARTH RESOURCE DATA SCIENCE 1: FUNDAMENTALS | 3.0 |
| GEOL558 | EARTH RESOURCE DATA SCIENCE 2: APPLICATIONS AND MACHINE-LEARNING | 3.0 |
| CEEN501 | LIFE CYCLE ASSESSMENT | 3.0 |
| DSCI503 | ADVANCED DATA SCIENCE | 3.0 |
| DSCI530 | STATISTICAL METHODS I | 3.0 |
| MNGN502 | GEOSPATIAL BIG DATA ANALYTICS | 3.0 |
| Students attending on campus also may select from semester based, in person courses GEGN532, GEGN568, CEEN581. | | |

## Program Director

Wendy Zhou, Professor, Geology & Geological Engineering

## Program Associate Director

Sebnem Duzgun, Professor, Fred Banfield Endowed Chair in Mining Engineering

## Professors

Sebnem Duzgun, Professor, Fred Banfield Endowed Chair in Mining Engineering

Amy Landis, Civil and Environmental Engineering, Professor, Mines Presidential Faculty Fellow for Access, Attainment & Diversity

Wendy Zhou, Professor, Geology & Geological Engineering

## Teaching Professor

Wendy Fisher, Computer Science, Teaching Professor

## Research Professor

Zane Jobe, Research Associate Professor, Chevron Center of Research Excellence Director, Geology & Geological Engineering

# Hydrologic Science and Engineering

## Program Description

Hydrologic Science and Engineering (HSE) is comprised of faculty from several different Mines departments and offers interdisciplinary graduate degrees in hydrology.

The program offers programs of study in fundamental hydrologic science and applied hydrology with engineering applications. Our program encompasses groundwater hydrology, surface-water hydrology, vadose-zone hydrology, watershed hydrology, contaminant transport and fate, contaminant remediation, hydrogeophysics, and water policy/law.

HSE requires a core study of formal graduate courses for all degrees. Programs of study are interdisciplinary in nature, and coursework is obtained from multiple departments at Mines and is approved for each student by the student's advisor and thesis committee.

## Contact

Program Director: Dave Benson

Hydrology.mines.edu

Program Coordinator: Rachel McDonald

## Program Requirements

**MS non-thesis**: 30 credits total, including a design course or independent study. (See a list of design courses below)

**MS thesis**: 30 credits total, consisting of 24 credits of coursework and 6 credits of thesis credit. Students must also write and orally defend a research thesis.

**PhD:** 72 total credits, consisting of coursework (at least 36 hours), and research (at least 24 hours). Students must also successfully complete qualifying examinations, write and defend a dissertation proposal, write and defend a doctoral dissertation, and are expected to submit the dissertation work for publication in scholarly journals.

## Thesis and Dissertation Committee Requirements

Students must meet the general requirements listed in the graduate bulletin section *Graduate Degrees and Requirements*. In addition, the student's advisor or co-advisor must be an HSE faculty member. For MS thesis students, at least two committee members must be members of the HSE faculty. For doctoral students, at least two faculty on the committee must be a member of the HSE faculty. For PhD committee the required at-large member must be from a Mines department outside the student's home department, and where applicable, outside the students minor department.

## Prerequisites

- Baccalaureate degree in a science or engineering discipline
- College calculus: two semesters required
- Differential equations: one semester required
- College physics: one semester required
- College chemistry: two semesters required
- College statistics: one semester required
- Fluid mechanics

Note that some prerequisites may be completed in the first few semesters of the graduate program if approved by the HSE director/program manager. Contact Rachel McDonald for questions at rmcdonald@mines.edu.

## Mines' Combined Undergraduate/Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

## Required Curriculum

Students will work with their academic advisors and graduate thesis committees to establish plans of study that best fit their individual interests and goals. Each student will develop and submit a plan of study to their advisor during the first semester of enrollment. Doctoral students may transfer in credits from an earned MS graduate program according to requirements listed in the Graduate Degrees and Requirements (p. 29) section of the graduate bulletin, and after approval by the student's thesis committee.

## Core Curriculum

Curriculum areas of emphasis consist of core courses, design/thesis, and electives. Core courses cover four areas of knowledge: Groundwater, Surface Water, Chemistry, and Contaminant Fate and Transport. Students can elect to take 9 **or** 12 credits of core curriculum depending on selected option below. Courses that meet core requirements include the following:

| | | |
|---|---|---|
| **Option #1 (9 credit hrs.)** | | |
| GEGN566 | GROUNDWATER ENGINEERING | 3.0 |
| GEGN582 | INTEGRATED SURFACE WATER HYDROLOGY | 3.0 |
| CEEN/GEGN587 | HYDROCHEMICAL AND TRANSPORT PROCESSES | 3.0 |
| **Option #2 (12 credit hrs.)** | | |
| GEGN566 | GROUNDWATER ENGINEERING | 3.0 |
| GEGN582 | INTEGRATED SURFACE WATER HYDROLOGY | 3.0 |
| CEEN550 | PRINCIPLES OF ENVIRONMENTAL CHEMISTRY | 3.0 |
| **AND Choose one of the following:** | | |
| CEEN584 | SUBSURFACE CONTAMINANT TRANSPORT (*) | 3.0 |
| CEEN580 | CHEMICAL FATE AND TRANSPORT IN THE ENVIRONMENT | 3.0 |

(*) Taught every other year.

A grade of B- or better is required in all core courses for graduation.

Students who have completed coursework for a previous degree that satisfies one of these requirements can get core curriculum requirements waived with the appropriate Waiver form and approval of advisor.

In addition, a fluid mechanics class is required for students to complete the HSE degree programs. If a student has previously taken a fluid mechanics course (for example as part of an undergraduate degree) then this requirement is met; if a student has not previously taken a fluid mechanics course this requirement can be satisfied by taking: GEGN/CEEN 585 – Fluid Mechanics for Hydrology.

## Design Courses

For non-thesis MS students, the following is a list of Design Courses that may be completed in lieu of an Independent Study:

| | | |
|---|---|---|
| CEEN515 | HILLSLOPE HYDROLOGY AND STABILITY | 3.0 |
| CEEN581 | WATERSHED SYSTEMS MODELING | 3.0 |
| CEEN575 | HAZARDOUS WASTE SITE REMEDIATION | 3.0 |
| CEEN584 | SUBSURFACE CONTAMINANT TRANSPORT | 3.0 |
| GEGN532 | GEOLOGICAL DATA ANALYSIS | 3.0 |
| GEGN575 | APPLICATIONS OF GEOGRAPHIC INFORMATION SYSTEMS | 3.0 |
| GEGN583 | MATHEMATICAL MODELING OF GROUNDWATER SYSTEMS | 3.0 |
| GEGN584 | FIELD METHODS IN HYDROLOGY | 3.0 |
| GEGN586 | NUMERICAL MODELING OF GEOCHEMICAL SYSTEMS | 3.0 |

## Elective Courses

Electives may be chosen from the approved list below or as approved by your advisor or thesis committee.

| | | |
|---|---|---|
| CEEN511 | UNSATURATED SOIL MECHANICS | 3.0 |
| CEEN512 | SOIL BEHAVIOR | 3.0 |
| CEEN515 | HILLSLOPE HYDROLOGY AND STABILITY | 3.0 |
| CEEN560 | MOLECULAR MICROBIAL ECOLOGY AND THE ENVIRONMENT | 3.0 |
| CEEN562 | ENVIRONMENTAL GEOMICROBIOLOGY | 3.0 |
| CEEN570 | WATER AND WASTEWATER TREATMENT | 3.0 |
| CEEN571 | ADVANCED WATER TREATMENT ENGINEERING AND WATER REUSE | 3.0 |
| CEEN575 | HAZARDOUS WASTE SITE REMEDIATION | 3.0 |
| CEEN581 | WATERSHED SYSTEMS MODELING | 3.0 |
| CEEN582 | VADOSE ZONE HYDROLOGY | 3.0 |
| GEGN532 | GEOLOGICAL DATA ANALYSIS | 3.0 |
| GEGN573 | GEOLOGICAL ENGINEERING SITE INVESTIGATION | 3.0 |
| GEGN575 | APPLICATIONS OF GEOGRAPHIC INFORMATION SYSTEMS | 3.0 |
| GEGN581 | ANALYTICAL HYDROLOGY | 3.0 |
| GEGN584 | FIELD METHODS IN HYDROLOGY | 3.0 |
| GEGN586 | NUMERICAL MODELING OF GEOCHEMICAL SYSTEMS | 3.0 |
| GEOL540 | ISOTOPE GEOCHEMISTRY AND GEOCHRONOLOGY | 3.0 |
| MATH530 | INTRODUCTION TO STATISTICAL METHODS | 3.0 |
| MATH531 | THEORY OF LINEAR MODELS | 3.0 |
| MATH532 | SPATIAL STATISTICS | 3.0 |
| EBGN510 | NATURAL RESOURCE ECONOMICS | 3.0 |
| HASS588 | GLOBAL WATER POLITICS AND POLICY | 3.0 |
| GEGN585 | FLUID MECHANICS FOR HYDROLOGY | 2.0 |

## Areas of specialization

Students may choose to complete an area of specialization within the MS in Hydrology degrees by taking additional defined courses. These areas of specialization are: Hydrogeophysics, Hydrobiogeochemistry, and Hydrology, Policy, and Management. The area of specialization will appear on the transcripts of students who register for and complete the required coursework. Courses required for these areas of specialization are:

### *1. Hydrogeophysics:*

| | | |
|---|---|---|
| GPGN574 | ADVANCED HYDROGEOPHYSICS | 3.0 |
| GPGN533 | GEOPHYSICAL DATA INTEGRATION & GEOSTATISTICS | 3.0 |
| GPGN570 | APPLICATIONS OF SATELLITE REMOTE SENSING | 3.0 |
| or GPGN520 | ELECTRICAL AND ELECTROMAGNETIC EXPLORATION | |

### *2. Hydrobiogeochemistry*

Students choose three of the following courses with at least one from each of microbiology-focused and geochemistry focused courses. Students with a Hydrobiogeochemistry area of specialization are encouraged to enroll in CEEN550 and a separate Contaminant Fate and Transport course (CEEN580 or CEEN584) to satisfy the HSE core, leaving GEGN586 and CEEN551 as the geochemistry focused courses.

| | | |
|---|---|---|
| **Microbiology Focus:** | | |
| CEEN562 | ENVIRONMENTAL GEOMICROBIOLOGY | 3.0 |
| CEEN560 | MOLECULAR MICROBIAL ECOLOGY AND THE ENVIRONMENT | 3.0 |
| **Geochemistry Focus:** | | |
| CEEN550 | PRINCIPLES OF ENVIRONMENTAL CHEMISTRY | 3.0 |
| GEGN586 | NUMERICAL MODELING OF GEOCHEMICAL SYSTEMS | 3.0 |
| CEEN551 | ENVIRONMENTAL ORGANIC CHEMISTRY | 3.0 |

### *3. Hydrology, Policy, and Management*

Students pursuing the Hydrology, Policy, and Management specialty track will choose two of the following three courses focused on water policy and management.

| | | |
|---|---|---|
| EBGN537 | ECONOMICS OF WATER | 3.0 |
| HASS588 | GLOBAL WATER POLITICS AND POLICY | 3.0 |
| HASS584 | US WATER POLITICS AND POLICY | 3.0 |

In addition, students will choose a third course from a broader list that also includes courses in complementary areas of communication, economics, law, philosophy, and policy. Current course options are listed below. Because course options are continually expanding, additional complementary courses (beyond those listed here) may be approved on an ad hoc basis by the coordinator of the Hydrology, Policy,

and Management track and the HSE program director in response to individual student requests.

| | | |
|---|---|---|
| EBGN537 | ECONOMICS OF WATER | 3.0 |
| EBGN570 | ENVIRONMENTAL ECONOMICS | 3.0 |
| HASS521 | ENVIRONMENTAL PHILOSOPHY | 3.0 |
| HASS523 | ADVANCED SCIENCE COMMUNICATION | 3.0 |
| HASS525 | ENVIRONMENTAL COMMUNICATION | 3.0 |
| HASS560 | GEOPOLITICS OF NATURAL RESOURCES | 3.0 |
| HASS565 | SCIENCE, TECHNOLOGY, AND SOCIETY | 3.0 |
| HASS568 | ENVIRONMENTAL JUSTICE | 3.0 |
| HASS588 | GLOBAL WATER POLITICS AND POLICY | 3.0 |
| HASS584 | US WATER POLITICS AND POLICY | 3.0 |
| HASS593 | NATURAL RESOURCES & ENERGY POLICY: THEORIES AND PRACTICE | 3.0 |
| MNGN571 | ENERGY, NATURAL RESOURCES, AND SOCIETY | 3.0 |
| PEGN530 | ENVIRONMENTAL LAW AND SUSTAINABILITY | 3.0 |

### Leadership

Eric Anderson, Civil & Environmental Engineering, HSE Associate Director

David Benson, HSE Director, Professor, Geology & Geological Engineering

### Department of Chemistry

James Ranville, Professor

Bettina Voelker, Professor

### Department of Civil & Environmental Engineering

Eric Anderson, Associate Professor

Christopher Higgins, Professor

Terri Hogue, Dean of Earth & Society Programs

Tissa Illangasekare, Professor and AMAX Distinguished Chair

Ning Lu, Professor

Junko Munakata Marr, Professor

John McCray, Professor

John Spear, Professor

### Department of Economics and Business

Steven M. Smith, Assistant Professor

### Department of Geology and Geological Engineering

Adrienne Marshall, Assistant Professor

Alexis Sitchler, Associate Professor

Danica Roth, Assistant Professor

Kamini Singha, Professor

Paul Santi, Professor

Reed Maxwell, Professor

Wendy Zhou, Professor

### Department of Geophysics

John Bradford, Vice President for Global Initiatives

Brandon Dugan, Professor and Baker Hughes Chair in Petrophysics & Borehole Geophysics and Associate Department Head GP

Matthew Siegfried, Assistant Professor

### Department of Humanities, Arts and Social Sciences

Hussein Amery, Professor

Adrianne Kroepsch, Assistant Professor

### Department of Mechanical Engineering

Nils Tilton, Associate Professor

### Department of Mining Engineering

Rennie Kaunda, Assistant Professor

### Department of Petroleum Engineering

Yu-Shu Wu, Professor

# Materials Science

### Degrees Offered

- Master of Science (Materials Science, thesis option or non-thesis option)
- Doctor of Philosophy (Materials Science)

### Program Description

The interdisciplinary graduate program in Materials Science exists to educate students, with at least a Bachelor of Science degree in engineering or science in the diverse field of Materials Science. This diversity includes the four key foundational aspects of Materials Science – materials properties including characterization and modeling, materials structures, materials synthesis and processing, and materials performance – as applied to materials of a variety of types (i.e., metals, ceramics, polymers, electronic materials and biomaterials). The Materials Science graduate program is responsible for administering MS (thesis and non-thesis) and PhD degrees in Materials Science.

This interdisciplinary degree program coexists alongside strong disciplinary programs in Chemistry, Chemical and Biochemical Engineering, Mechanical Engineering, Metallurgical and Materials Engineering, Mining, and Physics. The student's graduate committee will have final approval of the course of study.

## Fields of Research

- Advanced polymeric materials
- Alloy theory, concurrent design, theory-assisted materials engineering, and electronic structure theory
- Applications of artificial intelligence techniques to materials processing and manufacturing, neural networks for process modeling and sensor data processing, manufacturing process control
- Atomic scale characterization
- Atom Probe Tomography
- Biomaterials
- Ceramic processing, modeling of ceramic processing
- Characterization, thermal stability, and thermal degradation mechanisms of polymers
- Chemical and physical processing of materials, engineered materials, materials synthesis
- Chemical vapor deposition
- Coating materials and applications
- Computational condensed matter physics, semiconductor alloys, first-principles phonon calculations
- Computer modeling and simulation
- Control systems engineering, artificial neural systems for senior data processing, polymer cure monitoring sensors, process monitoring and control for composites manufacturing
- Crystal and molecular structure determination by X-ray crystallography
- Electrodeposition
- Electron and ion microscopy
- Energetic materials (explosives) and processing
- Energy storage
- Experimental condensed-matter physics, thermal and electrical properties of materials, superconductivity, photovoltaics
- Fuel cell materials
- Fullerene synthesis, combustion chemistry
- Heterogeneous catalysis, reformulated and alcohol fuels, surface analysis, electrophotography
- High-temperature ceramics
- Intelligent automated systems, intelligent process control, robotics, artificial neural systems
- Materials synthesis, interfaces, flocculation, fine particles
- Mathematical modeling of material processes
- Mechanical metallurgy, failure analysis, deformation of materials, advanced steel coatings
- Mechanical properties of ceramics and ceramic composites
- High entropy alloys
- Mössbauer spectroscopy, ion implantation, small-angle X-ray scattering, semiconductor defects
- Nano materials
- Nondestructive evaluation
- Nonferrous structural alloys
- Novel separation processes: membranes, catalytic membrane reactors, biopolymer adsorbents for heavy metal remediation of ground surface water
- Numerical modeling of particulate media, thermomechanical analysis
- Optical properties of materials and interfaces
- Phase transformations and mechanisms of microstructural change
- Photovoltaic materials and device processing
- Physical metallurgy, ferrous and nonferrous alloy systems
- Physical vapor deposition, thin films, coatings
- Power electronics, plasma physics, pulsed power, plasma material processing
- Processing and characterization of electroceramics (ferro-electrics, piezoelectrics, pyroelectrics, and dielectrics)
- Semiconductor materials and device processing
- Soft materials
- Solidification and near net shape processing
- Surface physics, epitaxial growth, interfacial science, adsorption
- Thermoelectric materials
- Transport phenomena and mathematical modeling
- Weld metallurgy, materials joining processes
- Welding and joining science

## Combined Degree Option

Mines undergraduate students have the opportunity to begin work on an MS non-thesis degree while concurrently completing their Bachelor's degree at Mines.

## Dual-Degree Program Option

Students have the opportunity to earn two degrees with the dual degree option. Students complete coursework to satisfy requirements for both a non-thesis MS in Materials Science from Colorado School of Mines and an MS of Physical Chemistry and Chemical Physics from the University of Bordeaux.

## Program Requirements

Each of the three degree programs (non-thesis MS, thesis-based MS, and PhD) require the successful completion of three core courses for a total of 9 credits that will be applied to the degree program course requirements. Depending upon the individual student's background, waivers for these courses may be approved by the program director. In order to gain a truly interdisciplinary understanding of Materials Science, students in the program are encouraged to select elective courses from several different departments outside of their home department regardless of the existence of a cross-listed MLGN course number. Course selection should be completed in consultation with the student's advisor and/or program director as appropriate.

## Mines' Combined Undergraduate / Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to six credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with "B-" or better, not be substitutes for required coursework, and meet all other University, Department, and Program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

Listed below are the three required Materials Science core courses:

| | | |
|---|---|---|
| MLGN591 | MATERIALS THERMODYNAMICS | 3.0 |
| MLGN592 | ADVANCED MATERIALS KINETICS AND TRANSPORT | 3.0 |
| MLGN593 | BONDING, STRUCTURE, AND CRYSTALLOGRAPHY | 3.0 |
| **Total Semester Hrs** | | **9.0** |

## Master of Science (Thesis Option)

The Master of Science degree requires a minimum of 30.0 credits of acceptable coursework and thesis research credits (see table below). The student must also submit a thesis and pass the Defense of Thesis examination before the Thesis Committee.

| | | |
|---|---|---|
| MLGN591 | MATERIALS THERMODYNAMICS | 3.0 |
| MLGN592 | ADVANCED MATERIALS KINETICS AND TRANSPORT | 3.0 |
| MLGN593 | BONDING, STRUCTURE, AND CRYSTALLOGRAPHY | 3.0 |
| ELECTIVES | Materials Science or Related Courses in any participating Materials Science department (AMFG, CBEN, CEEN, CHGN, DSCI, MEGN, MTGN) | 9.0 |
| MLGN707 | GRADUATE THESIS / DISSERTATION RESEARCH CREDIT | 12.0 |
| **Total Semester Hrs** | | **30.0** |

## Master of Science (Non-Thesis Option with a case study)

The Master of Science degree requires a minimum of 24.0 credits of acceptable course work and 6.0 additional credits of either case study or designated design course including:

| | | |
|---|---|---|
| MLGN591 | MATERIALS THERMODYNAMICS | 3.0 |
| MLGN592 | ADVANCED MATERIALS KINETICS AND TRANSPORT | 3.0 |
| MLGN593 | BONDING, STRUCTURE, AND CRYSTALLOGRAPHY | 3.0 |
| MLGN | Case Study OR Designated Design Courses *See table below | 6.0 |
| ELECTIVES | Materials Science or Related Courses in any participating Materials Science department (AMFG, CBEN, CEEN, CHGN, DSCI, MEGN, MTGN) | 15.0 |
| **Total Semester Hrs** | | **30.0** |

### *MLGN Design Courses

| | | |
|---|---|---|
| MLGN500 | PROCESSING, MICROSTRUCTURE, AND PROPERTIES OF MATERIALS | 3.0 |
| MLGN505 | MECHANICAL PROPERTIES OF MATERIALS | 3.0 |
| MLGN510 | SURFACE CHEMISTRY | 3.0 |
| MLGN516 | PROPERTIES OF CERAMICS | 3.0 |
| MLGN535 | INTERDISCIPLINARY MICROELECTRONICS PROCESSING LABORATORY | 3.0 |
| MLGN544 | ADVANCED PROCESSING OF CERAMICS | 3.0 |
| MLGN561 | TRANSPORT PHENOMENA IN MATERIALS PROCESSING | 3.0 |
| MLGN569 | FUEL CELL SCIENCE AND TECHNOLOGY | 3.0 |
| MLGN583 | PRINCIPLES AND APPLICATIONS OF SURFACE ANALYSIS TECHNIQUES | 3.0 |
| MLGN | Additional 500-level courses can be approved by MLGN Program Director | 3.0 |

## Doctor of Philosophy

The Doctor of Philosophy degree requires a minimum of 72.0 credits of course and research credit including:

| | | |
|---|---|---|
| MLGN591 | MATERIALS THERMODYNAMICS | 3.0 |
| MLGN592 | ADVANCED MATERIALS KINETICS AND TRANSPORT | 3.0 |
| MLGN593 | BONDING, STRUCTURE, AND CRYSTALLOGRAPHY | 3.0 |
| MLGN707 | GRADUATE THESIS / DISSERTATION RESEARCH CREDIT Minimum | 24.0 |
| ELECTIVES | Materials Science or Related Courses in any participating Materials Science department (AMFG, CBEN, CEEN, CHGN, DSCI, MEGN, MTGN) Minimum | 15.0 |
| MLGN | Thesis Research or Material Science Coursework | 24.0 |
| **Total Semester Hrs** | | **72.0** |

A minimum of 15 course credits earned at Mines is required for the PhD degree. In exceptional cases, this 15 Mines course credit requirement can be reduced in part or in full through the written consent of the student's advisor, program director, and thesis committee.

## PhD Qualifying Process

The following constitutes the qualifying processes by which doctoral students are admitted to candidacy in the Materials Science program.

Core Curriculum – The three required core classes must be completed in the first full academic year for all doctoral candidates. Students must obtain a grade of B or better in each class to be eligible to take the qualifying examination at the end of the succeeding summer semester. Students who do not meet the grade requirements may submit a written appeal to the program director by June 1st, outlining their rationale and providing any supporting documentation for the exemption. The graduate affairs committee will review the appeal on a case-by-case basis and will typically require the student to undertake additional assessments, independent study, or interviews to evidence their mastery of the subject matter. These remediations must be completed by the end of the summer semester following completion of the core classes.

PhD Qualifying Examination – A qualifying examination is given annually at the end of the summer semester under the direction of the Materials Science Graduate Affairs Committee. All first-year Materials Science PhD students are expected to successfully complete the qualifying examination to remain in good standing in the program.

The examination consists of a written report and an oral examination defending the written report. The written report should serve as a proposal for a research endeavor worthy of a single publication and discuss both the background that would motivate such an effort and the specific activities proposed. Students submit their research proposal to a panel of reviewers to include a member of the Materials Science Graduate Affairs Committee and one invited subject matter expert approved by the Materials Science Graduate Affairs Committee. The oral

examination will investigate the extent to which the student understands the background, motivation, and proposed work of their proposal.

If a student performs below the expectations of the Materials Science faculty on either component of the qualifying exam, they must revise their report and be re-examined by the end of the ensuing fall semester (typically month 15). Satisfactorily completing the oral exam will allow the student to proceed with the PhD program. Not passing the reexamination will lead to the student being removed from the PhD program. Additional details will be provided to the students by the program director including, exact dates, details expectations, and a rubric for grading. Upon completion of these steps and upon completion of all required coursework, candidates are admitted to candidacy.

PhD Thesis Proposal – While the proposal itself should focus on the central topic of a student's research efforts, during the proposal defense, candidates may expect to receive a wide range of questions from the Committee. This would include all manner of questions directly related to the proposal. Candidates, however, should also expect questions related to the major concept areas of Materials Science within the context of a candidate's research focus.

Following successful completion of coursework and the PhD qualifying process, candidates must also submit a thesis and successfully complete the PhD Defense of Thesis examination before the PhD Thesis Committee.

## Courses

**MLGN500. PROCESSING, MICROSTRUCTURE, AND PROPERTIES OF MATERIALS. 3.0 Semester Hrs.**
(II) A summary of the important relationships between the processing, microstructure, and properties of materials. Topics include electronic structure and bonding, crystal structures, lattice defects and mass transport, glasses, phase transformation, important materials processes, and properties including: mechanical and rheological, electrical conductivity, magnetic, dielectric, optical,
thermal, and chemical. In a given year, one of these topics will be given special emphasis. Another area of emphasis is phase equilibria. Prerequisite: none. 3 hours lecture; 3 semester hours.

**MLGN502. SOLID STATE PHYSICS. 3.0 Semester Hrs.**
An elementary study of the properties of solids including crystalline structure and its determination, lattice vibrations, electrons in metals, and semiconductors. 3 hours lecture; 3 semester hours. Prerequisite: PH320.

**MLGN505. MECHANICAL PROPERTIES OF MATERIALS. 3.0 Semester Hrs.**
(I) Mechanical properties and relationships. Plastic deformation of crystalline materials. Relationships of microstructures to mechanical strength. Fracture, creep, and fatigue. Prerequisite: MTGN348. 3 hours lecture; 3 hours lab; 3/4 semester hours. *This is a 3 credit-hour graduate course in the Materials Science Program and a 4 credit-hour undergraduate-course in the MTGN program.

**MLGN510. SURFACE CHEMISTRY. 3.0 Semester Hrs.**
Introduction to colloid systems, capillarity, surface tension and contact angle, adsorption from solution, micelles and microemulsions, the solid/gas interface, surface analytical techniques, Van Der Waal forces, electrical properties and colloid stability, some specific colloid systems (clays, foams and emulsions). Students enrolled for graduate credit in MLGN510 must complete a special project.

**MLGN512. CERAMIC ENGINEERING. 3.0 Semester Hrs.**
(II) Application of engineering principles to nonmetallic and ceramic materials. Processing of raw materials and production of ceramic bodies, glazes, glasses, enamels, and cements. Firing processes and reactions in glass bonded as well as mechanically bonded systems. Prerequisite: MTGN348. 3 hours. lecture; 3 semester hours.

**MLGN515. ELECTRICAL PROPERTIES AND APPLICATIONS OF MATERIALS. 3.0 Semester Hrs.**
(II) Survey of the electrical properties of materials, and the applications of materials as electrical circuit components. The effects of chemistry, processing, and microstructure on the electrical properties will be discussed, along with functions, performance requirements, and testing methods of materials for each type of circuit component. The general topics covered are conductors, resistors, insulators, capacitors, energy convertors, magnetic materials, and integrated circuits. Prerequisites: PHGN200; MTGN311 or MLGN501; MTGN412/MLGN512,. 3 hours lecture; 3 semester hours.

**MLGN516. PROPERTIES OF CERAMICS. 3.0 Semester Hrs.**
(II) A survey of the properties of ceramic materials and how these properties are determined by the chemical structure (composition), crystal structure, and the microstructure of crystalline ceramics and glasses. Thermal, optical, and mechanical properties of single-phase and multi-phase ceramics, including composites, are covered. Prerequisites: PHGN200, MTGN311 or MLGN501, MTGN412. 3 semester hours: 3 hours lecture.

**MLGN517. THEORY OF ELASTICITY. 3.0 Semester Hrs.**
This is a graduate course that builds upon the learning outcomes of Continuum Mechanics course to introduce students the fundamentals of Theory of Elasticity. Introduction is realized through theory development, application examples, and numerical solutions. Learning outcomes from this course would be essential to further studies in visco-elasticity and plasticity. Knowledge from this course will enable students to work on variety of engineering applications in Mechanical, Materials, Aerospace, Civil and related engineering fields. This course is cross-listed with MEGN510.
**Course Learning Outcomes**

- Recall definitions for indicial notation, transformation rules for tensors, and eigenvalue problems. Tensor algebra and tensor calculus.
- Define, and apply, displacement-strain relationships. Strain measurements using strain gauges and rosettes. Calculate principal strains, maximum shear strain in 3D.
- Establish the definitions, and use, stress tensor, traction vector, normal, and shear tractions. Find stresses at a point on a given plane, principal stresses and max shear stress.
- State the general three-dimensional constitutive law for linear elastic materials. Define material symmetry and the engineering notation stiffness matrix for materials with monoclinic, orthotropic, transversely isotropic, cubic symmetry.
- Define, and apply, the generalized form of Hooke's Law for isotropic materials.
- State, and apply, the field equations for linear isotropic elasticity.
- Write clear and complete boundary condition statement.
- Use the semi-inverse method to find solutions for two dimensional elasticity problems.
- Use the Airy stress function to find solutions for two dimensional elasticity problems.
- Define, and apply, yield theories (von Mises and Tresca) for isotropic solids.
- Use the Prandtl stress function to find solutions for torsional elasticity problems.

**MLGN519. NON-CRYSTALLINE MATERIALS. 3.0 Semester Hrs.**
(I) An introduction to the principles of glass science and engineering and non-crystalline materials in general. Glass formation, structure, crystallization and properties will be covered, along with a survey of commercial glass compositions, manufacturing processes and applications. Prerequisites: MTGN311 or MLGN501; MLGN512/ MTGN412. 3 hours lecture; 3 semester hours.

**MLGN530. INTRODUCTION TO POLYMER SCIENCE. 3.0 Semester Hrs.**
Chemistry and thermodynamics of polymers and polymer solutions. Reaction engineering of polymerization. Characterization techniques based on solution properties. Materials science of polymers in varying physical states. Processing operations for polymeric materials and use in separations. Prerequisite: CHGN221, MATH225, CHEN357. 3 hour lecture, 3 semester hours.

**MLGN531. POLYMER ENGINEERING AND TECHNOLOGY. 3.0 Semester Hrs.**
(II) This class provides a background in polymer fluid mechanics, polymer rheological response and polymer shape forming. The class begins with a discussion of the definition and measurement of material properties. Interrelationships among the material response functions are elucidated and relevant correlations between experimental data and material response in real flow situations are given. Processing operations for polymeric materials will then be addressed. These include the flow of polymers through circular, slit, and complex dies. Fiber spinning, film blowing, extrusion and co-extrusion will be covered as will injection molding. Graduate students are required to write a term paper and take separate examinations which are at a more advanced level. Prerequisite: CRGN307, EGGN351 or equivalent. 3 hours lecture; 3 semester hours.

**MLGN535. INTERDISCIPLINARY MICROELECTRONICS PROCESSING LABORATORY. 0-3 Semester Hr.**
Equivalent with
CBEN435,CBEN535,CHEN435,CHEN535,PHGN435,PHGN535,
(II) Application of science and engineering principles to the design, fabrication, and testing of microelectronic devices. Emphasis on specific unit operations and the interrelation among processing steps. Prerequisite: none. 3 hours lecture; 3 semester hours.

**MLGN536. ADVANCED POLYMER SYNTHESIS. 3.0 Semester Hrs.**
(II) An advanced course in the synthesis of macromolecules. Various methods of polymerization will be discussed with an emphasis on the specifics concerning the syntheses of different classes of organic and inorganic polymers. Prerequisite: CHGN430, ChEN415, MLGN530. 3 hours lecture, 3 semester hours.

**MLGN544. ADVANCED PROCESSING OF CERAMICS. 3.0 Semester Hrs.**
A description of the principles of ceramic processing and the relationship between processing and microstructure. Raw materials and raw material preparation, forming and fabrication, thermal processing, and finishing of ceramic materials will be covered. Principles will be illustrated by case studies on specific ceramic materials. A project to design a ceramic fabrication process is required. Prerequisite: MTGN314.

**MLGN561. TRANSPORT PHENOMENA IN MATERIALS PROCESSING. 3.0 Semester Hrs.**
(II) Fluid flow, heat and mass transfer applied to processing of materials. Rheology of polymers, liquid metal/particles slurries, and particulate solids. Transient flow behavior of these materials in various geometries, including infiltration of liquids in porous media. Mixing and blending. Flow behavior of jets, drainage of films and particle fluidization. Surface-tension-, electromagnetic-, and bubble-driven flows. Heat -transfer behavior in porous bodies applied to sintering and solidification of composites. Simultaneous heat-and-mass-transfer applied to spray drying and drying porous bodies. Prerequisites: ChEN307 or ChEN308 or MTGN461. 3 hours lecture; 3 semester hours.

**MLGN563. POLYMER ENGINEERING: STRUCTURE, PROPERTIES AND PROCESSING. 3.0 Semester Hrs.**
(II) An introduction to the structure and properties of polymeric materials, their deformation and failure mechanisms, and the design and fabrication of polymeric end items. The molecular and crystallographic structures of polymers will be developed and related to the elastic, viscoelastic, yield and fracture properties of polymeric solids and reinforced polymer composites. Emphasis will be placed on forming techniques for end item fabrication including: extrusion, injection molding, reaction injection molding, thermoforming, and blow molding. The design of end items will be considered in relation to: materials selection, manufacturing engineering, properties, and applications. Prerequisite: MTGN311 or equivalent. 3 hours lecture; 3 semester hours.

**MLGN565. MECHANICAL PROPERTIES OF CERAMICS AND COMPOSITES. 3.0 Semester Hrs.**
(II) Mechanical properties of ceramics and ceramic-based composites; brittle fracture of solids; toughening mechanisms in composites; fatigue, high temperature mechanical behavior, including fracture, creep deformation. Prerequisites: MTGN445 or MLGN505. 3 hours lecture; 3 semester hours. (Fall of even years only.).

**MLGN569. FUEL CELL SCIENCE AND TECHNOLOGY. 3.0 Semester Hrs.**
Equivalent with MTGN569,
(II) Investigate fundamentals of fuel-call operation and electrochemistry from a chemical thermodynamics and materials science perspective. Review types of fuel cells, fuel-processing requirements and approaches, and fuel-cell system integration. Examine current topics in fuel-cell science and technology. Fabricate and test operational fuel cells in the Colorado Fuel Cell Center. Prerequisites: EGGN371 or ChEN357 or MTGN351 Thermodynamics I, MATH225 Differential
Equations. 3 credit hours.

**MLGN570. BIOCOMPATIBILITY OF MATERIALS. 3.0 Semester Hrs.**
(II) Introduction to the diversity of biomaterials and applications through examination of the physiologic environment in conjunction with compositional and structural requirements of tissues and organs. Appropriate domains and applications of metals, ceramics and polymers, including implants, sensors, drug delivery, laboratory automation, and tissue engineering are presented. Prerequisites: ESGN 301 or equivalent. 3 hours lecture; 3 semester hours.

**MLGN572. BIOMATERIALS. 3.0 Semester Hrs.**
Equivalent with MTGN572,
A broad overview on materials science and engineering principles for biomedical applications with three main topics: 1) The fundamental properties of biomaterials; 2) The fundamental concepts in biology; 3) The interactions between biological systems with exogenous materials. Examples including surface energy and surface modification; protein adsorption; cell adhesion, spreading and migration; biomaterials implantation and acute inflammation; blood-materials interactions and thrombosis; biofilm and biomaterials-related pathological reactions. Basic principles of bio-mimetic materials synthesis and assembly will also be introduced. 3 hours lecture; 3 semester hours.

**MLGN583. PRINCIPLES AND APPLICATIONS OF SURFACE ANALYSIS TECHNIQUES. 3.0 Semester Hrs.**
(II) Instrumental techniques for the characterization of surfaces of solid materials. Applications of such techniques to polymers, corrosion, metallurgy, adhesion science, micro-electronics. Methods of analysis discussed: X-ray photoelectron spectroscopy (XPS), auger electron

spectroscopy (AES), ion scattering spectroscopy (ISS), secondary ion mass spectroscopy (SIMS), Rutherford backscattering (RBS), scanning and transmission electron microscopy (SEM, TEM), energy and wavelength dispersive X-ray analysis; principles of these methods, quantification, instrumentation, sample preparation. Prerequisite: B.S. in metallurgy, chemistry, chemical engineering, physics. 3 hours lecture; 3 semester hours. This course taught in alternate even numbered years.

**MLGN591. MATERIALS THERMODYNAMICS. 3.0 Semester Hrs.**
A review of the thermodynamic principles of work, energy, entropy, free energy, equilibrium, and phase transformations in single and multi-component systems. Students will apply these principles to a broad range of materials systems of current importance including solid state materials, magnetic and piezoelectric materials, alloys, chemical and electrochemical systems, soft and biological materials and nanomaterials. Prerequisite: 300 level thermodynamics, multivariable calculus and differential equations, introductory college chemistry, and introductory materials science courses or consent of instructor.

**MLGN592. ADVANCED MATERIALS KINETICS AND TRANSPORT. 3.0 Semester Hrs.**
A broad treatment of homogenous and heterogeneous kinetic transport and reaction processes in the gas, liquid, and solid states, with a specific emphasis on heterogeneous kinetic processes involving gas/solid, liquid/solid, and solid/solid systems. Reaction rate theory, nucleation and growth, and phase transformations will be discussed. A detailed overview of mass, heat, and charge transport in condensed phases is provided including a description of fundamental transport mechanisms, the development of general transport equations, and their application to a number of example systems. Prerequisite: 300 level thermodynamics, multivariable calculus and differential equations, introductory college chemistry, and introductory materials science courses or consent of instructor.

**MLGN593. BONDING, STRUCTURE, AND CRYSTALLOGRAPHY. 3.0 Semester Hrs.**
This course will be an overview of condensed matter structure from the atomic scale to the mesoscale. Students will gain a perspective on electronic structure as it relates to bonding, long range order as it relates to crystallography and amorphous structures, and extend these ideas to nanostructure and microstructure. Examples relating to each hierarchy of structure will be stressed, especially as they relate to reactivity, mechanical properties, and electronic and optical properties. Prerequisite: 300 level thermodynamics, multivariable calculus and differential equations, introductory college chemistry, and introductory materials science courses or consent of instructor.

**MLGN597. CASE STUDY - MATERIALS SCIENCE. 0.5-6 Semester Hr.**
Individual research or special problem projects supervised by a faculty member.
**Course Learning Outcomes**

- Graduates will demonstrate the ability to conduct directed research; the ability to assimilate and assess scholarship; and the ability to apply scholarship in new, creative and productive ways.

**MLGN598. SPECIAL TOPICS. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

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**MLGN599. CASE STUDY MATERIALS SCIENCE. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree. Prerequisite: Independent Study form must be completed and submitted to the Registrar.

**MLGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

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**MLGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**MLGN607. CONDENSED MATTER. 3.0 Semester Hrs.**
(I) Principles and applications of the quantum theory of electronic in solids: structure and symmetry, electron states and excitations in metals; transport properties. Prerequisite: PHGN520 and PHGN440/MLGN502. 3 hours lecture; 3 semester hours.

**MLGN698. SPECIAL TOPICS. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**MLGN699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**MLGN699. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**MLGN707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.**
(I, II, S) Research credit hours required for completion of a Masters-level thesis or Doctoral dissertation. Research must be carried out under the

direct supervision of the student's faculty advisor. Variable class and semester hours. Repeatable for credit.

## Program Directors

Eric Toberer, , Associate Professor, Physics

Brian Trewyn, Associate Professor, Chemistry

## Department of Chemical and Biological Engineering

Moises Carreon, Professor

Matthew Crane, Assistant Professor

Diego Gomez Gualdron, Assistant Professor

Andrew Herring, Professor

Carolyn Koh, Professor

Melissa Krebs, Associate Professor

Ramya Kumar, Assistant Professor

Stephanie Kwon, Assistant Professor

David Marr, Professor

Joseph Samaniuk, Assistant Professor

Colin Wolden, Professor

David Wu, Professor

## Department of Chemistry

Dylan Domaille, Assistant Professor

Tom Gennett, Professor and Department Head

Dan Knauss, Professor

Annalise Maughan, Assistant Professor

C. Michael McGuirk, Assistant Professor

Christine Morrison, Assistant Professor

Svitlana Pylypenko, Associate Professor

Ryan Richards, Professor

Alan Sellinger, Professor

Jenifer Shafer, Associate Professor

Brian Trewyn, Associate Professor

Bettina Voelker, Professor

Kim Williams, Professor

David Wu, Professor

## Department of Civil and Environmental Engineering

Timothy Strathmann, Professor

Lori Tunstall, Assistant Professor

## Department of Geology and Geological Engineering

Alexis Navarre-Sitchler, Associate Professor

## Department of Mechanical Engineering

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Steven DeCaluwe, Associate Professor

Veronica Eliasson, Associate Professor

Joy Gockel, Associate Professor

Owen Hildreth, Associate Professor

Greg Jackson, Professor

Robert Kee, Professor

Leslie Lamberson, Associate Professor

Neal Sullivan, Associate Professor

Brian Thomas, Professor

Xiaoli Zhang, Associate Professor

## Department of Metallurgical and Materials Engineering

Gerald Bourne, Teaching Professor

Geoff Brennecka, Associate Professor

Amy Clarke, Professor

Kester Clarke, Associate Professor

Robert Cryderman, Research Associate Professor

Kip Findley, Associate Professor

Brian Gorman, Associate Professor

Megan Holtz, Assistant Professor

Michael Kaufman, Professor

Jeffrey King, Professor

Jonah Klemm-Toole, Assistant Professor

Suveen Mathaudhu, Professor

Vladan Stevanovic, Associate Professor

## Department of Physics

Serena Eley, Assistant Professor

Tim Ohno, Associate Professor

Meenakshi Singh, Assistant Professor

Eric Toberer, Associate Professor and Program Director

Jeramy Zimmerman, Associate Professor

## Professors Emeriti

Thomas E. Furtak, Department of Physics

Stephen Liu, Department of Metallurgical and Materials Engineering

Brajendra Mishra, Department of Metallurgical and Materials Engineering

P. Craig Taylor, Department of Physics

Steven Thompson, Department of Metallurgical and Materials Engineering

Chester J. Van Tyne, Department of Metallurgical and Materials Engineering

J. Douglas Way, Department of Chemical and Biological Engineering

# Nuclear Engineering

## Program Description

The Nuclear Science and Engineering program at Colorado School of Mines is interdisciplinary in nature and draws contributions from departments across the university. While delivering a traditional Nuclear Engineering course core, the School of Mines program in Nuclear Science and Engineering emphasizes the nuclear fuel life cycle. Faculty bring to the program expertise in all aspects of the nuclear fuel life cycle: fuel exploration and processing, nuclear power systems production, design and operation, fuel recycling, storage and waste remediation, radiation detection, and radiation damage as well as the policy issues surrounding each of these activities. Students in all three Nuclear Engineering degrees are exposed to a broad systems overview of the complete nuclear fuel cycle as well as obtaining detailed expertise in a particular component of the cycle. Related research is conducted through the Nuclear Science and Engineering Center with facilities for making advanced measurements on fuel cycle related radioactive materials up to the heaviest reactor-produced element fermium as well as access to the 1 MW GSTR reactor. Students who graduate from the program are prepared for careers in sustainable nuclear energy production, design and analysis of nuclear systems including nuclear reactors, isotope production and purification, national security, or nuclear research.

## Student Learning Outcomes

By the end of their nuclear engineering curriculum, students should be able to:

1. Apply fundamentals of nuclear science and engineering in solving open-ended problems

2. Use modern tools of nuclear measurement, analysis, and modeling

3. Locate and use pertinent information from the nuclear literature

4. Interpret and use experimental data for nuclear systems

5. Effectively communicate in both written and oral formats

6. Make responsible contributions to society

## Contact

Mark Jensen

nuclear.mines.edu

## Program Requirements

The Nuclear Science and Engineering Program offers programs of study leading to three graduate degrees:

## Master of Engineering (ME)

| | |
|---|---|
| Core courses | 13.0 |
| Elective core courses | 12.0 |
| Additional elective courses | 3.0 |
| Nuclear Science and Engineering Seminar | 2.0 |
| **Total Semester Hrs** | **30.0** |

## Master of Science (MS)

| | |
|---|---|
| Core courses | 13.0 |
| Elective core courses | 6.0 |
| Nuclear Science and Engineering Seminar | 2.0 |
| Graduate research (minimum) | 6.0 |
| Graduate research or elective courses | 3.0 |
| **Total Semester Hrs** | **30.0** |

MS students must complete and defend a research thesis in accordance with this Graduate catalog and the Nuclear Science and Engineering Thesis Procedures. The student must complete the preparation and defense of a thesis proposal as described by the Nuclear Science and Engineering Proposal Procedures at least one semester before the student defends his or her MS thesis.

## Doctor of Philosophy (PhD)

| | |
|---|---|
| Core courses | 13.0 |
| Elective core courses | 12.0 |
| Additional elective courses | 3.0 |
| Nuclear Science and Engineering Seminar | 4.0 |
| Graduate research (minimum) | 24.0 |
| Graduate research or elective courses | 16.0 |
| **Total Semester Hrs** | **72.0** |

PhD students must successfully complete the program's quality control process.

The PhD quality control process includes the following:

- Prior to admission to candidacy, the student must complete all of the Nuclear Engineering required core and elective core classes.
- Prior to admission to candidacy, the student must pass a qualifying examination in accordance with the Nuclear Science and Engineering Qualifying Exam Procedures.
- A PhD thesis proposal must be presented to, and accepted by, the student's thesis committee in accordance with the Nuclear Science and Engineering Proposal Procedures.
- The student must complete and defend a PhD thesis in accordance with this Graduate catalog and the Nuclear Science and Engineering Thesis Procedures.

## Thesis Committee Requirements

The student's thesis committee must meet the general requirements listed in the Graduate Bulletin section on Graduate Degrees and

Requirements (p. 29). In addition, the student's advisor or co-advisor must be an active faculty member of Mines Nuclear Science and Engineering Program. For MS students, at least two, and for PhD students, at least three, committee members must be faculty members of the Nuclear Science and Engineering Program and must come from at least two different departments. At least one member of the PhD committee must be a faculty member from outside the Nuclear Science and Engineering Program.

## Required Curriculum

In order to be admitted to the Nuclear Science and Engineering Graduate Degree Program, students must meet the following minimum requirements:

- Baccalaureate degree in a science or engineering discipline from an accredited program
- Mathematics coursework up to and including differential equations
- Coursework in thermodynamics
- ENGY475 (or equivalent).

Students who do not meet these minimum requirements may be admitted with specified coursework to be completed in the first semesters of the graduate program. These introductory courses will be selected in consultation with the student's graduate advisor.

All degree offerings within the Nuclear Science and Engineering program are based on a set of required and elective core courses. The required core classes are:

| | | |
|---|---|---|
| NUGN510 | INTRODUCTION TO NUCLEAR REACTOR PHYSICS | 3.0 |
| NUGN520 | INTRODUCTION TO NUCLEAR REACTOR THERMAL-HYDRAULICS | 3.0 |
| NUGN580 | NUCLEAR REACTOR LABORATORY (taught in collaboration with the USGS) | 3.0 |
| NUGN585 & NUGN586 | NUCLEAR REACTOR DESIGN I and NUCLEAR REACTOR DESIGN II | 4.0 |
| **Total Semester Hrs** | | **13.0** |

Additionally, students pursuing a Nuclear Engineering graduate degree must take a certain number of courses from the elective core (four for a ME or PhD, two for an MS). The core electives consist of the following:

| | | |
|---|---|---|
| MTGN593 | NUCLEAR MATERIALS SCIENCE AND ENGINEERING | 3.0 |
| PHGN504 | RADIATION DETECTION AND MEASUREMENT | 3.0 |
| CHGN511 | APPLIED RADIOCHEMISTRY | 3.0 |
| CHGN513 | CHEMISTRY OF THE LANTHANIDES AND ACTINIDES | |
| MEGN592 | RISK AND RELIABILITY ENGINEERING ANALYSIS AND DESIGN | 3.0 |
| NUGN506 | NUCLEAR FUEL CYCLE | 3.0 |
| NUGN590 | COMPUTATIONAL REACTOR PHYSICS | 3.0 |
| PHGN598 | SPECIAL TOPICS | 0-6 |

Additionally, a 500-level Nuclear Physics class counts toward the credits required to fulfill core elective requirements. This is optional for Master's degrees but required for a PhD degree.

Students will select additional coursework in consultation with their graduate advisor and their thesis committee (where applicable). Through these additional courses, students gain breadth and depth in their knowledge the Nuclear Engineering industry.

Students seeking MS and PhD degrees are required to complete the minimum research credit requirements ultimately leading to the completion and defense of a thesis. Research is conducted under the direction of a member of Mines Nuclear Science and Engineering faculty and could be tied to a research opportunity provided by industry partners.

## Graduate Seminar

Full-time graduate students in the Nuclear Science and Engineering Program are expected to maintain continuous enrollment in Nuclear Science and Engineering Seminar. Students who are concurrently enrolled in a different degree program that also requires seminar attendance may have this requirement waived at the discretion of the program director.

## Mines' Combined Undergraduate/Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

## Minor Degree Programs

Students majoring in allied fields may choose to complete minor degree programs through the Nuclear Science and Engineering Program indicating specialization in a nuclear-related area of expertise. Minor programs require completion of 9 credits of approved coursework (masters degree), or 12 credits of approved coursework (PhD). Existing minors and their requirements are as follows, with the first three courses listed being required for a masters degree, and the last being an additional requirement for a PhD degree:

## Nuclear Engineering

| | | |
|---|---|---|
| NUGN510 | INTRODUCTION TO NUCLEAR REACTOR PHYSICS | 3.0 |
| NUGN520 | INTRODUCTION TO NUCLEAR REACTOR THERMAL-HYDRAULICS | 3.0 |
| NUGN580 | NUCLEAR REACTOR LABORATORY | 3.0 |
| MTGN598 | SPECIAL TOPICS IN METALLURGICAL AND MATERIALS ENGINEERING (Nuclear Materials Politics and Public Policy) | 3.0 |
| **Total Semester Hrs** | | **12.0** |

## Nuclear Materials Processing

| | | |
|---|---|---|
| NUGN510 | INTRODUCTION TO NUCLEAR REACTOR PHYSICS | 3.0 |
| MTGN593 | NUCLEAR MATERIALS SCIENCE AND ENGINEERING | 3.0 |
| NUGN506 | NUCLEAR FUEL CYCLE | 3.0 |

| | | |
|---|---|---|
| CHGN511 | APPLIED RADIOCHEMISTRY | 3.0 |
| or MTGN598 | SPECIAL TOPICS IN METALLURGICAL AND MATERIALS ENGINEERING | |
| **Total Semester Hrs** | | **12.0** |

## Nuclear Detection

| | | |
|---|---|---|
| NUGN510 | INTRODUCTION TO NUCLEAR REACTOR PHYSICS | 3.0 |
| PHGN504 | RADIATION DETECTION AND MEASUREMENT | 3.0 |
| NUGN580 | NUCLEAR REACTOR LABORATORY | 3.0 |
| PHGN598 | SPECIAL TOPICS | 6.0 |
| **Total Semester Hrs** | | **15.0** |

## Courses

**NUGN505. NUCLEAR SCIENCE AND ENGINEERING SEMINAR. 1.0 Semester Hr.**
(I, II) The Nuclear Science and Engineering Seminar provides a forum for Nuclear Engineering graduate students to present their research projects, participate in seminars given by Nuclear Science and Engineering professionals, and develop an enhanced understanding of the breadth of the nuclear engineering discipline. Prerequsite: gradaute standing. 1 hour seminar; 1 semester hour. Repeatable; maximum 2 hours granted towards M.S./M.E. Degree Requirements and 4 hours maximum granted towards Ph.D. Requirements.

**NUGN506. NUCLEAR FUEL CYCLE. 3.0 Semester Hrs.**
(I) An introduction to nuclear energy emphasizing the science, engineering, and policies underlying the systems and processes involved in energy production by nuclear fission. Students will acquire a broad understanding of nuclear energy systems framed in the context of the fuel used to power nuclear reactors. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Use Segré chart to determine properties of various nuclides
- Describe the components of various nuclear fuel cycles and their interrelation
- Determine the cost of nuclear fuel under a variety of economic and technical conditions
- Distinguish between various fissile nuclides and their importance as reactor fuel or nuclear explosives
- Perform and apply basic power reactor calculations such as isotope production rates, average flux, reactor power, capacity factor, fuel burnup, efficiency of multibatch cores.
- . Recount the basic chemical and engineering considerations in the milling of uranium bearing ores and the reprocessing of used nuclear fuel
- Describe major regulations affecting nuclear waste disposal in the US and their impact on disposal strategies
- Describe the major features of a waste repository and consider how they intersect with the requirements imposed by the composition of used nuclear fuel.

**NUGN507. MATH METHODS IN NUCLEAR. 1.0 Semester Hr.**

**NUGN510. INTRODUCTION TO NUCLEAR REACTOR PHYSICS. 3.0 Semester Hrs.**
Bridges the gap between courses in fundamental nuclear physics and the neutronic design and analysis of nuclear reactors. Review of neutron energetics and reactions; nuclear cross sections; neutron induced fission; neutron life cycle, multiplication, and criticality; nuclear reactor kinetics and control; the diffusion approximation for neutron transport; simple reactor geometries and compositions; modeling and simulation of reactors. Prerequisite: ENGY475, MEGN475 or equivalent.

**NUGN520. INTRODUCTION TO NUCLEAR REACTOR THERMAL-HYDRAULICS. 3.0 Semester Hrs.**
Bridges the gap between fundamental courses in thermodynamics, fluid flow, and heat transer and the thermal-hydraulic design and analysis of nuclear reactors. Provides a comprehensive introduction to the thermal-hydraulics of each of the major classes of nuclear reactors. Introduces the major thermal-hydraulic computational tools, passively safe reactor design, thermal-hydraulic transient analysis, and severe nuclear reactor accident analysis. Prerequisite: ENGY475, MEGN475 or equivalent.

**NUGN535. INTRODUCTION TO HEALTH PHYSICS. 3.0 Semester Hrs.**
(I) Health physics evaluates effects of ionizing radiation on biological systems for the safe use of radiation and control of potential health hazards. The core concept is dosimetry, which relates the radiation absorbed externally and internally to a quantitative estimate of health effects. Other areas in health physics such as protection standards, regulations, and radiation diagnosis and therapy are all constructed on dosimetric methods.

**NUGN570. MATHEMATICAL METHODS IN NUCLEAR SCIENCE AND ENGINEERING. 1.0 Semester Hr.**
This is a 1 credit course in the applied mathematics of nuclear engineering. Students will be instructed in how to solve systems of coupled ODEs and PDEs describing neutron transport and burnup. Students will also learn how to use adjoint perturbation theory to investigate stability in nuclear reactors, and how to use Python to formulate numerical solutions to neutron transport and burnup equations. Examples will be drawn specifically from nuclear reactor physics and nuclear thermal hydraulics.
**Course Learning Outcomes**

- Use matrix exponentials and Laplace transforms to solve linear modified burnup equations
- Identify linear PDEs and ODEs that come up in modeling nuclear reactors
- Use Python for numerical solutions of the neutron diffusion equation
- Use Python for the coupled solution of neutron diffusion and burnup equations in a 1-D reactor
- Understand the derivation of the modified Bateman equations used to model burnup in a nuclear reactor
- Solve the time dependent neutron diffusion equation in 1-3 dimensions
- Use perturbation theory to understand stability in the non-linear neutron diffusion equation
- Define and solve adjoint equations

**NUGN580. NUCLEAR REACTOR LABORATORY. 3.0 Semester Hrs.**
Provides hands-on experience with a number of nuclear reactor operations topics. Reactor power calibration; gamma spectroscopy; neutron activation analysis; reactor flux and power profiles; reactor criticality; control rod worth; xenon transients and burnout; reactor pulsing. Taught at the USGS TRIGA reactor. Prerequisite: NUGN510. 3 hours laboratory; 3 semester hours.

**NUGN585. NUCLEAR REACTOR DESIGN I. 2.0 Semester Hrs.**
Provides a basic understanding of the nuclear reactor design process, including: key features of nuclear reactors; nuclear reactor design principles; identification of design drivers; neutronic and thermal-hydraulic

design of nuclear reactors; reactor safety considerations; relevant nuclear engineering computer codes. Prerequisite: NUGN510, NUGN520.

**NUGN586. NUCLEAR REACTOR DESIGN II. 2.0 Semester Hrs.**
Builds on the design experience obtained in NUGN586 to provide an in-depth
understanding of the nuclear reactor design process. Prerequisites: NUGN585 (taken in the same academic year). 2 hours lecture; 2 semester hours.

**NUGN590. COMPUTATIONAL REACTOR PHYSICS. 3.0 Semester Hrs.**
(I) This course will provide an introduction to computational nuclear reactor physics. Students will understand the physics driving neutron cross sections and how they determined, and how neutron transport calculations are completed using Monte Carlo and finite difference methods. Students will learn how to write modular code using professional software engineering practices, and will have an introduction to the Serpent and MCNP family of transport codes. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Students should understand the physics driving reactor operation and implement this understanding to address nuclear engineering challenges.

**NUGN598. SPECIAL TOPICS. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**NUGN598. SPECIAL TOPICS. 0-6 Semester Hr.**

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**NUGN598. SPECIAL TOPICS. 0-6 Semester Hr.**

**NUGN599. INDEPENDENT STUDY IN NUCLEAR ENGINEERING. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

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**NUGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**NUGN599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**NUGN698. SPECIAL TOPICS. 0-6 Semester Hr.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**NUGN699. INDEPENDENT STUDY IN NUCLEAR ENGINEERING. 0.5-6 Semester Hr.**
(I, II, S) Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Prerequisite: “Independent Study” form must be completed and submitted to the Registrar. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**NUGN707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.**
(I, II, S) Research credit hours required for completion of a Masters-level thesis or Doctoral dissertation. Research must be carried out under the direct supervision of the student's faculty advisor. Variable class and semester hours. Repeatable for credit.

## Program Director

Mark Jensen, Jerry and Tina Grandey University Chair in Nuclear Science and Engineering, Department of Chemistry

## Department of Chemical and Biological Engineering

Colin Wolden, Professor and William K. Coors Distinguished Chair

## Department of Chemistry

Mark Jensen, Professor and Jerry and Tina Grandey University Chair in Nuclear Science and Engineering

Thomas Albrecht, Distinguished University Professor, Nuclear Science and Engineering Center Director

Jenifer Shafer, Professor

## Department of Economics and Business

Roderick Eggert, Professor

## Department of Mechanical Engineering

Mark Deinert, Associate Professor

Andrew Osborne, Assistant Professor

## Department of Metallurgical and Materials Engineering

Kip Findley, Professor

Jeffrey King, Professor

Suveen Mathaudhu, Professor

Ivar Reimanis, Professor and George S. Ansell Chair

Haitao Dong, Radiation Safety Officer

## Department of Physics

Uwe Greife, Professor

Kyle Leach, Associate Professor

Frederic Sarazin, Professor

# Operations Research with Engineering

## Program Description

Operations Research involves mathematically modeling physical systems (both naturally occurring and man-made) with a view to determining

a course of action for the system to either improve or optimize its functionality. Examples of such systems include: manufacturing systems, chemical processes, socioeconomic systems, mechanical systems (e.g., those that produce and utilize energy and materials), and mining systems. The ORwE Program allows students to complete an interdisciplinary master's (non-thesis) or doctoral-level degree by taking courses and conducting research in the following departments and divisions: Applied Mathematics and Statistics, Civil and Environmental Engineering, Electrical Engineering, Computer Science, Economics and Business, Mining Engineering, Mechanical Engineering, and Metallurgical & Materials Engineering. Operations Research presence at Mines is ubiquitous, especially in Mines' focus areas of earth, energy and the environment.

## Student Learning Outcomes

- Apply principles of optimization, stochastic modeling and simulation to real-world engineering situations.
- Mathematically formulate operations research models.
- Use state-of-the-art software to determine solutions to optimization, stochastics and simulation models.

## Contact

DH Alexandra M. Newman

Program Website

## Program Requirements

## Master of Science in Operations Research with Engineering (non-thesis)

| | |
|---|---|
| Core Courses | 18.0 |
| ORWE courses not taken as core courses | 12.0 |
| Total | 30.0 |

All master's students are required to take a set of core courses (18 credits) that provides basic tools for the more advanced and specialized courses in the program as specified below.

| | | |
|---|---|---|
| MEGN502 | ADVANCED ENGINEERING ANALYSIS | 3.0 |
| or ORWE598 | ALGORITHMS FOR OPERATIONS RESEARCH | |
| or CEEN505 | NUMERICAL METHODS FOR ENGINEERS | |
| EBGN526 | STOCHASTIC MODELS IN MANAGEMENT SCIENCE | 3.0 |
| or MATH538 | STOCHASTIC MODELS | |
| EBGN528 | INDUSTRIAL SYSTEMS SIMULATION | 3.0 |
| MATH530 | INTRODUCTION TO STATISTICAL METHODS | 3.0 |
| ORWE586 | LINEAR OPTIMIZATION | 3.0 |
| or ORWE585 | NETWORK MODELS | |
| ORWE587 | NONLINEAR OPTIMIZATION | 3.0 |
| or ORWE588 | INTEGER OPTIMIZATION | |

The remaining 12 credits of coursework can be completed with any ORWE-labeled course not taken as core. Or specialty tracks can be added in areas, for example, including: 1) operations research methodology, 2) systems engineering, 3) computer science, 4) finance and economics, and 5) an existing engineering discipline that is reflected in a department name such as electrical, civil, environmental, or mining engineering.

Students who do not wish to specialize in a track mentioned in the table below and do not wish to complete 12 additional credits of ORWE-labeled coursework can mix and match from the ORWE coursework and coursework mentioned in the tables below in consultation with and approval from their academic advisers.

Examples of specialty tracks from various departments across campus are given below:

## Energy Systems within Mechanical Engineering Track (12 credits from the course list below)

| | | |
|---|---|---|
| MEGN567 | PRINCIPLES OF BUILDING SCIENCE | |
| AMFG501 | ADDITIVE MANUFACTURING | 3.0 |
| MEGN570 | ELECTROCHEMICAL SYSTEMS ENGINEERING | |
| MEGN560 | DESIGN AND SIMULATION OF THERMAL SYSTEMS | 3.0 |
| MEGN561 | ADVANCED ENGINEERING THERMODYNAMICS | 3.0 |

## Additive Manufacturing Track (12 credits from the course list below)*

*Subject to approval by graduate council

| | | |
|---|---|---|
| AMFG511 | DATA DRIVEN ADVANCED MANUFACTURING | 3.0 |
| AMFG521 | DESIGN FOR ADDITIVE MANUFACTURING | 3.0 |
| AMFG531 | MATERIALS FOR ADDITIVE MANUFACTURING | 3.0 |
| AMFG501 | ADDITIVE MANUFACTURING | 3.0 |

## Applied Mathematics and Statistics Track (12 credits from the course list below)

| | | |
|---|---|---|
| MATH500 | LINEAR VECTOR SPACES | 3.0 |
| MATH532 | SPATIAL STATISTICS | 3.0 |
| MATH536 | ADVANCED STATISTICAL MODELING | 3.0 |
| MATH537/538 | MULTIVARIATE ANALYSIS | 3.0 |
| MATH551 | COMPUTATIONAL LINEAR ALGEBRA | 3.0 |
| EENG511 | CONVEX OPTIMIZATION AND ITS ENGINEERING APPLICATIONS | |

## Economics Track (12 credits from the course list below)

| | | |
|---|---|---|
| EBGN509 | MATHEMATICAL ECONOMICS | 3.0 |
| EBGN510 | NATURAL RESOURCE ECONOMICS | 3.0 |
| EBGN530 | ECONOMICS OF INTERNATIONAL ENERGY MARKETS | 3.0 |
| EBGN535 | ECONOMICS OF METAL INDUSTRIES AND MARKETS | 3.0 |
| EBGN590 | ECONOMETRICS I | 3.0 |
| EBGN645 | COMPUTATIONAL ECONOMICS | 3.0 |
| CSCI555 | GAME THEORY AND NETWORKS | 3.0 |

## Business Track (12 credits from the course list below)

| | | |
|---|---|---|
| ORWE559 | SUPPLY CHAIN MANAGEMENT | 3.0 |
| EBGN560 | DECISION ANALYTICS | 3.0 |
| EBGN571 | MARKETING ANALYTICS | 3.0 |
| EBGN562 | STRATEGIC DECISION MAKING | 3.0 |

## Computer Science Track (12 credits from the course list below)

| | | |
|---|---|---|
| CSCI542 | SIMULATION | 3.0 |
| CSCI562 | APPLIED ALGORITHMS AND DATA STRUCTURES | 3.0 |
| CSCI571 | ARTIFICIAL INTELLIGENCE | 3.0 |
| CSCI575 | ADVANCED MACHINE LEARNING | 3.0 |
| CSCI555 | GAME THEORY AND NETWORKS | 3.0 |

## Civil Engineering - Geotechnics Track (12 credits from the course list below)

| | | |
|---|---|---|
| CEEN506 | FINITE ELEMENT METHODS FOR ENGINEERS | 3.0 |
| CEEN510 | ADVANCED SOIL MECHANICS | 3.0 |
| CEEN519 | RISK ASSESSMENT IN GEOTECHNICAL ENGINEERING | 3.0 |
| CEEN511 | UNSATURATED SOIL MECHANICS | 3.0 |
| CEEN512 | SOIL BEHAVIOR | 3.0 |
| CEEN515 | HILLSLOPE HYDROLOGY AND STABILITY | 3.0 |

## Civil Engineering-Structures Track (12 credits from the course list below)

| | | |
|---|---|---|
| CEEN506 | FINITE ELEMENT METHODS FOR ENGINEERS | 3.0 |
| CEEN530 | ADVANCED STRUCTURAL ANALYSIS | 3.0 |
| CEEN531 | STRUCTURAL DYNAMICS | 3.0 |
| CEEN533 | MATRIX STRUCTURAL ANALYSIS | 3.0 |
| CEEN543 | ADVANCED DESIGN OF STEEL STRUCTURES | 3.0 |
| CEEN545 | STEEL BRIDGE DESIGN | 3.0 |

## Nuclear Engineering Track (12 credits from the course list below)

| | | |
|---|---|---|
| NUGN506 | NUCLEAR FUEL CYCLE | 3.0 |
| NUGN510 | INTRODUCTION TO NUCLEAR REACTOR PHYSICS | 3.0 |
| NUGN520 | INTRODUCTION TO NUCLEAR REACTOR THERMAL-HYDRAULICS | 3.0 |
| NUGN580 | NUCLEAR REACTOR LABORATORY | 3.0 |
| NUGN590 | COMPUTATIONAL REACTOR PHYSICS | 3.0 |
| NUGN585/586 | NUCLEAR REACTOR DESIGN I | 2.0 |

## Electrical Engineering-Antennas and Wireless Communications Track (12 credits from the course list below)

| | | |
|---|---|---|
| EENG525 | ANTENNAS | |
| EENG527 | WIRELESS COMMUNICATIONS | |
| EENG530 | PASSIVE RF & MICROWAVE DEVICES | |
| EENG526 | ADVANCED ELECTROMAGNETICS | |
| EENG528 | COMPUTATIONAL ELECTROMAGNETICS | |

## Electrical Engineering-Energy Systems and Power Electronics Track (9 credits from the course list below)

| | | |
|---|---|---|
| EENG570 | ADVANCED HIGH POWER ELECTRONICS | 3.0 |
| EENG580 | POWER DISTRIBUTION SYSTEMS ENGINEERING | 3.0 |
| EENG581 | POWER SYSTEM OPERATION AND MANAGEMENT | 3.0 |

## Electrical Engineering-Information and Systems Sciences Track (12 credits from the course list below)

| | | |
|---|---|---|
| EENG509 | SPARSE SIGNAL PROCESSING | 3.0 |
| EENG511 | CONVEX OPTIMIZATION AND ITS ENGINEERING APPLICATIONS | |
| EENG515 | MATHEMATICAL METHODS FOR SIGNALS AND SYSTEMS | 3.0 |
| EENG517 | THEORY AND DESIGN OF ADVANCED CONTROL SYSTEMS | 3.0 |
| EENG519 | ESTIMATION THEORY AND KALMAN FILTERING | 3.0 |
| EENG527 | WIRELESS COMMUNICATIONS | |
| EENG589 | DESIGN AND CONTROL OF WIND ENERGY SYSTEMS | 3.0 |
| MEGN544 | ROBOT MECHANICS: KINEMATICS, DYNAMICS, AND CONTROL | 3.0 |

## Mining and Earth Systems Track (12 credits from the course list below)

| | | |
|---|---|---|
| MNGN502 | GEOSPATIAL BIG DATA ANALYTICS | 3.0 |
| MNGN512 | SURFACE MINE DESIGN | 3.0 |
| MNGN516 | UNDERGROUND MINE DESIGN | 3.0 |
| MNGN536 | OPERATIONS RESEARCH TECHNIQUES IN THE MINERAL INDUSTRY | 3.0 |
| MNGN539 | ADVANCED MINING GEOSTATISTICS | 3.0 |

## Doctor of Philosophy in Operations Research with Engineering

The ORWE PhD allows students to complete an interdisciplinary doctoral degree in Operations Research with Engineering by taking courses and conducting research in eight departments/divisions: Applied Mathematics and Statistics, Electrical Engineering, Computer Sciences, Civil and Environmental Engineering, Economics and Business, Mining Engineering, Mechanical Engineering, and Metallurgical and Materials Engineering.

## Specialty Requirements

Doctoral students develop a customized curriculum to fit their needs. The degree requires a minimum of 72 graduate credits that includes coursework and a thesis. Coursework is valid for nine years toward a

PhD degree; any exceptions must be approved by the director of the ORWE program and by the student's adviser.

## Credit requirements

| | |
|---|---|
| Core Courses | 24.0 |
| Area of Specialization Courses | 12.0 |
| Any Combination of Specialization Courses or Research | 12.0 |
| Research Credits | 24.0 |
| **Total Semester Hrs** | **72.0** |

## Research Credits

Students must complete at least 24 research credits. The student's faculty adviser and the doctoral thesis committee must approve the student's program of study and the topic for the thesis.

## Qualifying Examination Process and Thesis Proposal

Upon completion of the appropriate core coursework, students must pass Qualifying Exams I (written, over four courses) and II (oral, consisting of a report and research presentation) to become a candidate for the PhD, ORWE specialty. Qualifying Exam I is generally taken no later than three semesters after entry into the PhD program, and Qualifying Exam II follows no more than two semesters after passing Qualifying Exam I. The proposal defense should be completed within ten months of passing Qualifying Exam II.

## Transfer Credits

Students may transfer up to 24 credits of graduate-level coursework from other institutions toward the PhD degree subject to the restriction that those courses must not have been used as credit toward a bachelor's degree. The student must have achieved a grade of B or better in all graduate transfer courses and the transfer must be approved by the student's doctoral thesis committee and the Director of the ORWE program.

Although most doctoral students will only be allowed to transfer up to 24 credits, with approval from the student's doctoral committee, exceptions may be made to allow students who have earned a specialized thesis-based master's degree in operations research or other closely related field from another university to transfer up to 36 credits in recognition of the degree. Students should consult with their academic advisors and ORWE director for details.

## Unsatisfactory Progress

In addition to the institutional guidelines for unsatisfactory progress as described elsewhere in this bulletin, unsatisfactory progress will be assigned to any full-time student who does not pass the following prerequisite and core courses in the first three semesters of study:

| | | |
|---|---|---|
| CSCI262 | DATA STRUCTURES | 3.0 |
| ORWE586 | LINEAR OPTIMIZATION | 3.0 |
| ORWE598 | ALGORITHMS FOR OPERATIONS RESEARCH | 3.0 |
| EBGN526 | STOCHASTIC MODELS IN MANAGEMENT SCIENCE | 3.0 |

Unsatisfactory progress will also be assigned to any students who do not complete requirements as specified in their admission letters. Any exceptions to the stipulations for unsatisfactory progress must be approved by the ORWE committee. Part-time students develop an approved course plan with their advisor.

## Prerequisites

Students must complete the following undergraduate prerequisite courses with a grade of B or better:

| | | |
|---|---|---|
| CSCI128 | COMPUTER SCIENCE FOR STEM | 3.0 |
| CSCI200 | FOUNDATIONAL PROGRAMMING CONCEPTS & DESIGN | 3.0 |
| CSCI220 | DATA STRUCTURES AND ALGORITHMS | 3.0 |

Required Course Curriculum

All PhD students are required to take a set of core courses that provides basic tools for the more advanced and specialized courses in the program.

| Core Courses | | |
|---|---|---|
| ORWE598 | ALGORITHMS FOR OPERATIONS RESEARCH | 3.0 |
| MEGN502 | ADVANCED ENGINEERING ANALYSIS | 3.0 |
| ORWE586 | LINEAR OPTIMIZATION | 3.0 |
| MATH530 | INTRODUCTION TO STATISTICAL METHODS | 3.0 |
| ORWE585 | NETWORK MODELS | 3.0 |
| ORWE588 | INTEGER OPTIMIZATION | 3.0 |
| ORWE587 | NONLINEAR OPTIMIZATION | 3.0 |
| EBGN526 | STOCHASTIC MODELS IN MANAGEMENT SCIENCE | 3.0 |
| **Total Semester Hrs** | | **24.0** |

Students are required to take four courses from the following list:

| Area of Specialization Courses | | |
|---|---|---|
| CSCI555 | GAME THEORY AND NETWORKS | 3.0 |
| CSCI562 | APPLIED ALGORITHMS AND DATA STRUCTURES | 3.0 |
| EBGN509 | MATHEMATICAL ECONOMICS | 3.0 |
| EBGN528 | INDUSTRIAL SYSTEMS SIMULATION | 3.0 |
| or CSCI542 | SIMULATION | |
| EBGN560 | DECISION ANALYTICS | 3.0 |
| EBGN575 | ADVANCED MINING AND ENERGY ASSET VALUATION | 3.0 |
| EENG517 | THEORY AND DESIGN OF ADVANCED CONTROL SYSTEMS | 3.0 |
| MATH531 | THEORY OF LINEAR MODELS | 3.0 |
| MATH532 | SPATIAL STATISTICS | 3.0 |
| MATH537 | MULTIVARIATE ANALYSIS | 3.0 |
| MATH582 | STATISTICS PRACTICUM | 3.0 |
| MEGN592 | RISK AND RELIABILITY ENGINEERING ANALYSIS AND DESIGN | 3.0 |
| MNGN536 | OPERATIONS RESEARCH TECHNIQUES IN THE MINERAL INDUSTRY | 3.0 |
| MNGN538 | GEOSTATISTICAL ORE RESERVE ESTIMATION | 3.0 |
| ORWE688 | ADVANCED INTEGER OPTIMIZATION | 3.0 |
| ORWE686 | ADVANCED LINEAR OPTIMIZATION | 3.0 |

| | | |
|---|---|---|
| 5XX/6XX | Special Topics (Requires approval of the advisor and OrwE program director) | 3.0 |

## Mines' Combined Undergraduate/Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

## Courses

**ORWE559. SUPPLY CHAIN MANAGEMENT. 3.0 Semester Hrs.**
(II) Due to the continuous improvement of information technology, shorter life cycle of products, rapid global expansion, and growing strategic relationships, supply chain management has become a critical asset in today's organizations to stay competitive. The supply chain includes all product, service and information flow from raw material suppliers to end customers. This course focuses on the fundamental concepts and strategies in supply chain management such as inventory management and risk pooling strategies, distribution strategies, make-to-order/make-to-stock supply chains, supplier relationships and strategic partnerships. It introduces quantitative tools to model, optimize and analyze various decisions in supply chains as well as real-world supply chain cases to analyze the challenges and solutions. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Understand fundamental supply chain management concepts such as inventory management, supply chain planning, integration, distribution and coordination"
- Understand challenges that arise in supply chains
- Understand the role of optimization models that are used to model supply chain operations and solve them using AMPL
- Analyze supply chains of different businesses and discuss possible solutions to their problems.

**ORWE585. NETWORK MODELS. 3.0 Semester Hrs.**
(I) We examine network flow models that arise in manufacturing, energy, mining, transportation and logistics: minimum cost flow models in transportation, shortest path problems in assigning inspection effort on a manufacturing line, and maximum flow models to allocate machine-hours to jobs. We also discuss an algorithm or two applicable to each problem class. Computer use for modeling (in a language such as AMPL) and solving (with software such as CPLEX) these optimization problems is introduced. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- 1. Understand how to differentiate spanning tree, shortest path, maximum flow and minimum cost flow models.
- 2. Understand how to graphically depict and mathematically model spanning tree, shortest path, maximum flow and minimum cost flow models.
- 3. Understand algorithms that solve model spanning tree, shortest path, maximum flow and minimum cost flow models.
- 4. Understand the difference between network and non-network optimization models

**ORWE586. LINEAR OPTIMIZATION. 3.0 Semester Hrs.**
(I) We address the formulation of linear programming models, linear programs in two dimensions, standard form, the Simplex method, duality theory, complementary slackness conditions, sensitivity analysis, and multi-objective programming. Applications of linear programming models include, but are not limited to, the areas of manufacturing, energy, mining, transportation and logistics, and the military. Computer use for modeling (in a language such as AMPL) and solving (with software such as CPLEX) these optimization problems is introduced. Offered every other year. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Understand how to formulate linear optimization models
- Understand how to solve linear optimization models, both by hand and with the computer through an algebraic modeling language and a state-of-the-art solver.
- Understand the special structure underlying linear optimization models and how this affects their ability to be solved.
- Understand sensitivity and post-optimality analysis.

**ORWE587. NONLINEAR OPTIMIZATION. 3.0 Semester Hrs.**
(I) This course addresses both unconstrained and constrained nonlinear model formulation and corresponding algorithms (e.g., Gradient Search and Newton's Method, and Lagrange Multiplier Methods and Reduced Gradient Algorithms, respectively). Applications of state-of-the-art hardware and software will emphasize solving real-world engineering problems in areas such as manufacturing, energy, mining, transportation and logistics, and the military. Computer use for modeling (in a language such as AMPL) and solving (with an algorithm such as MINOS) these optimization problems is introduced. Offered every other year. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Understand how to formulate nonlinear optimization models.
- Understand how to solve nonlinear optimization models, both by hand and with the computer through an algebraic modeling language and a state-of-the-art solver.
- Understand the special structure underlying nonlinear optimization models and how this affects their ability to be solved.

**ORWE588. INTEGER OPTIMIZATION. 3.0 Semester Hrs.**
(I) This course addresses the formulation of integer programming models, the branch-and-bound algorithm, total unimodularity and the ease with which these models are solved, and then suggest methods to increase tractability, including cuts, strong formulations, and decomposition techniques, e.g., Lagrangian relaxation, Benders decomposition. Applications include manufacturing, energy, mining, transportation and logistics, and the military. Computer use for modeling (in a language such as AMPL) and solving (with software such as CPLEX) these optimization problems is introduced. Offered every other year. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Understand how to formulate linear-integer optimization models.
- Understand how to solve linear-integer optimization models, both by hand and with the computer through an algebraic modeling language and a state-of-the-art solver.

- Understand the special structure underlying linear-integer optimization models and how this affects their ability to be solved.
- Understand decomposition techniques to aid in solution.

**ORWE598. SPECIAL TOPICS. 0-6 Semester Hr.**

**ORWE598. ALGORITHMS FOR OPERATIONS RESEARCH. 0-6 Semester Hr.**
Reasoning about algorithm correctness (proofs, counterexamples). Analysis of algorithms: asymptotic and practical complexity. Review of dictionary data structures (including balanced search trees). Priority queues. Advanced sorting algorithms (heapsort, radix sort). Advanced algorithmic concepts illustrated through sorting (randomized algorithms, lower bounds, divide and conquer). Dynamic programming. Backtracking. Algorithms on unweighted graphs (traversals) and weighted graphs (minimum spanning trees, shortest paths, network flows and bipartite matching); NP-completeness and its consequences. Prerequisite: CSCI220 with a grade of C- or higher or CSCI262 with a grade of C- or higher, MATH213 or MATH223 or MATH224, MATH300 or MATH358 or CSCI358.
**Course Learning Outcomes**

- Same as existing CSCI406.

**ORWE598. SIMULATION FOR OPERATIONS RESEARCH. 3.0 Semester Hrs.**
A first course in computer simulation using formal learning groups and emphasizing the rigorous development of simulation applications. Topics will include random number generation, Monte Carlo simulation, discrete event simulation, and the mathematics behind their proper implementation and analysis (random variates, arrival time modeling, infinite horizon statistics, batch means and sampling techniques). The course uses learning group assignments, quizzes, programming projects (using Linux) and exams for assessment. Prerequisite: (CSCI210 or CSCI274) AND CSCI306 AND (MATH201 or MATH334).
**Course Learning Outcomes**

- same as existing course CSCI423

**ORWE599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**

**ORWE686. ADVANCED LINEAR OPTIMIZATION. 3.0 Semester Hrs.**
(II) As an advanced course in optimization, we expand upon topics in linear programming: advanced formulation, the dual simplex method, the interior point method, algorithmic tuning for linear programs (including numerical stability considerations), column generation, and Dantzig-Wolfe decomposition. Time permitting, dynamic programming is introduced. Applications of state-of-the-art hardware and software emphasize solving real-world problems in areas such as manufacturing, mining, energy, transportation and logistics, and the military. Computers are used for model formulation and solution. Offered every other year. Prerequisite: MEGN586. 3 hours lecture; 3 semester hours.
**Course Learning Outcomes**

- Understand how to formulate complicated linear optimization models.
- Dual Simplex Method and Interior Point Method
- Algorithmic Tuning
- Column Generation and Dantzig-Wolfe Decomposition

**ORWE688. ADVANCED INTEGER OPTIMIZATION. 3.0 Semester Hrs.**
(II) As an advanced course in optimization, we expand upon topics in integer programming: advanced formulation, strong integer programming formulations (e.g., symmetry elimination, variable elimination, persistence), in-depth mixed integer programming cuts, rounding heuristics, constraint programming, and decompositions. Applications of state-of-the-art hardware and software emphasize solving real-world problems in areas such as manufacturing, mining, energy, transportation and logistics, and the military. Computers are used for model formulation and solution. Prerequisite: MEGN588. 3 hours lecture; 3 semester hours. Offered every other year.
**Course Learning Outcomes**

- Know how to formulate advanced integer optimization models 2. Be familiar with advanced algorithms to solve these models 3. Be able to use software, including scripting, to model and solve these models 4. Understand the theory behind and mathematical tenants of advanced integer optimization models

## Program Director

Alexandra Newman, Professor, Mechanical Engineering

# Quantitative Biosciences and Engineering

## Degrees Offered

- Master of Science in Quantitative Biosciences and Engineering (non-thesis)
- Master of Science in Quantitative Biosciences and Engineering (thesis)
- Doctor of Philosophy in Quantitative Biosciences and Engineering

## Program Description

The graduate program in quantitative biosciences and engineering brings together faculty across the Mines campus working on diverse areas of biology to educate students with at least a Bachelor of Science degree in engineering or science in the diverse field of biology. Biology deals broadly with life on this planet, the human organism and its health, and harnessing biological processes to produce fuels, chemicals, and consumer products. Thus, biology in general and human health and well-being in particular are important application areas for virtually all other areas of science, technology, and engineering. This is reflected in the fact that any academic discipline exists today with a bio prefix, such as biophysics, biochemistry, bioengineering, mathematical biology, computational biology, systems biology, structural biology, biomedicine, biomaterials, biomechanics, bioinformatics, biological chemistry, geobiology, environmental biology, microbiology, to name just a few. Similarly, health is included in many labels, e.g., digital healthcare, health economics, and health informatics. Educating students at the interfaces of biology, health, and engineering with other disciplines is a primary goal of this program.

Many departments at Mines jointly administer this cross-departmental program in quantitative biosciences and engineering. The program coexists alongside strong disciplinary programs, in chemistry and geochemistry, chemical and biochemical engineering, physics, computer science, mathematics and statistics, mechanical engineering and metallurgical and materials engineering, civil and environmental engineering, economics, geology, and geological engineering and geophysics, and thus draws from the strengths of these programs through close links and joint courses. For administrative purposes, at the graduate level, the student will reside in the advisor’s home academic

department. The student's graduate committee will have final approval of the course of study.

## Fields of Research

Research at Mines in this rapidly growing field currently includes but is not limited to the following general areas:

- Laser Design and Imaging
- Biofuels and Metabolic Engineering
- Omics and Systems Biology
- Environmental Toxicology and Microbiology
- Biosensors and Devices
- Biotechnology
- Biomechanics
- Biofluid mechanics
- Bioinformatics and Computational Biology
- Tissue Engineering & Biomaterials
- Physical Biochemistry
- Biophysics and Analytical Methodology Development
- Digital Healthcare
- Mathematical Biology

More than 35 faculty members across the Mines campus participate in this program, which will in the future also involve faculty of nearby collaborating institutions and scientists from the biotech/healthcare industry.

## Quantitative Biosciences and Engineering (QBE) Program Requirements

For admission, students may enter with biology or health-related undergraduate degrees or with a technical degree, e.g., in engineering, mathematics, or computer science.

Current Mines undergraduate students have the option to apply to the Office of Graduate Studies for the combined program while pursuing their undergraduate degree (see information below).

Each of the three degrees (non-thesis Master of Science, thesis-based Master of Science, and Doctor of Philosophy) require the successful completion of four core courses for a total of 13 credits, as detailed below.

| QBE Core Courses | | |
|---|---|---|
| BIOL500 | CELL BIOLOGY AND BIOCHEMISTRY | 4.0 |
| BIOL510 | BIOINFORMATICS | 3.0 |
| BIOL520 | SYSTEMS BIOLOGY | 3.0 |
| CHGN535 | PHYSICAL BIOCHEMISTRY | 3.0 |
| **Total Semester Hrs** | | **13.0** |

## QBE Graduate Seminar

Full-time graduate students in the QBE program are expected to maintain continuous enrollment in BIOL 590, QBE Graduate Seminar, a 1 credit course. A maximum of 2 credits will be granted toward the MS degree requirements while a maximum of 4 credits will be granted toward PhD requirements, as shown below. Students who are concurrently enrolled in a different degree program that also requires seminar attendance may have this requirement waived at the discretion of the QBE Program Director.

## Master of Science in Quantitative Biosciences and Engineering (Non-Thesis Option)

The Master of Science Non-Thesis (MS-NT) degree requires a minimum of 30 credits of acceptable coursework.

| | | |
|---|---|---|
| QBE Core Courses | | 13.0 |
| QBE Electives (see list below) | | 15.0 |
| BIOL590 | QUANTITATIVE BIOSCIENCES & ENGINEERING GRADUATE SEMINAR (*) | 2.0 |
| **Total Semester Hrs** | | **30.0** |

*While full-time MS-NT students are expected to maintain continuous enrollment in BIOL 590, the QBE Graduate Seminar; a maximum of 2 credits will be granted toward the MS-NT degree requirements.

## Master of Science in Quantitative Biosciences and Engineering (Thesis Option)

The thesis-based Master of Science (MS-T) requires a minimum of 30 semester hours of acceptable coursework and thesis research credits. Students conduct an in-depth research project with one of the participating faculty members who are currently accepting masters degree students. The student must also submit a thesis and pass the thesis defense examination before the thesis committee.

| | | |
|---|---|---|
| QBE Core Courses | | 13.0 |
| QBE Elective | | 3.0 |
| BIOL590 | QUANTITATIVE BIOSCIENCES & ENGINEERING GRADUATE SEMINAR (*) | 2.0 |
| BIOL707 | GRADUATE THESIS / DISSERTATION RESEARCH CREDIT | 12.0 |
| **Total Semester Hrs** | | **30.0** |

*While full-time MS-T students are expected to maintain continuous enrollment in BIOL 590, the QBE Graduate Seminar; a maximum of 2 credits will be granted toward the MS-T degree requirements.

## Doctor of Philosophy in Quantitative Biosciences and Engineering

The Doctor of Philosophy (PhD)degree requires a minimum of 72 hours of course and research credit including at least 24 credits in coursework and at least 24 credits in research. Doctoral students must also pass a qualifying examination and thesis-proposal defense, complete a satisfactory thesis, and successfully defend their thesis.

| | | |
|---|---|---|
| QBE Core Courses | | 13.0 |
| QBE Electives | | 11.0 |

| | | |
|---|---|---|
| BIOL590 | QUANTITATIVE BIOSCIENCES & ENGINEERING GRADUATE SEMINAR (*) | 4.0 |
| BIOL707 | GRADUATE THESIS / DISSERTATION RESEARCH CREDIT | 24.0 |
| QBE Electives or BIOL707 Research | | 20.0 |
| **Total Semester Hrs** | | **72.0** |

*While full-time PhD students are expected to maintain continuous enrollment in BIOL 590, the QBE Graduate Seminar, a maximum of 4 credits will be granted toward the PhD degree requirements.

**QBE Elective Courses:**

The current list of available electives is shown below. Because course options are continually expanding, additional complementary courses (beyond those listed here) may be approved on an ad hoc basis by the advisor in consultation with the program director.

| | | |
|---|---|---|
| BIOL599 | INDEPENDENT STUDY | 0.5-6 |
| CBEN505 | NUMERICAL METHODS IN CHEMICAL ENGINEERING | 3.0 |
| CBEN511 | NEUROSCIENCE, MEMORY, AND LEARNING | 3.0 |
| CBEN531 | IMMUNOLOGY FOR SCIENTISTS AND ENGINEERS | 3.0 |
| CBEN532 | TRANSPORT PHENOMENA IN BIOLOGICAL SYSTEMS | 3.0 |
| CBEN570 | INTRODUCTION TO MICROFLUIDICS | 3.0 |
| CBEN624 | APPLIED STATISTICAL MECHANICS | 3.0 |
| CBEN625 | MOLECULAR SIMULATION | 3.0 |
| CEEN501 | LIFE CYCLE ASSESSMENT | 3.0 |
| CEEN551 | ENVIRONMENTAL ORGANIC CHEMISTRY | 3.0 |
| CEEN560 | MOLECULAR MICROBIAL ECOLOGY AND THE ENVIRONMENT | 3.0 |
| CEEN562 | ENVIRONMENTAL GEOMICROBIOLOGY | 3.0 |
| CEEN566 | MICROBIAL PROCESSES, ANALYSIS AND MODELING | 3.0 |
| CEEN570 | WATER AND WASTEWATER TREATMENT | 3.0 |
| CHGN509 | BIOLOGICAL INORGANIC CHEMISTRY | 3.0 |
| CHGN507 | ADVANCED ANALYTICAL CHEMISTRY | 3.0 |
| CSCI562 | APPLIED ALGORITHMS AND DATA STRUCTURES | 3.0 |
| CSCI575 | ADVANCED MACHINE LEARNING | 3.0 |
| EBGN525 | BUSINESS ANALYTICS | 3.0 |
| EBGN553 | PROJECT MANAGEMENT | 3.0 |
| MATH530 | INTRODUCTION TO STATISTICAL METHODS | 3.0 |
| MATH572 | MATHEMATICAL AND COMPUTATIONAL NEUROSCIENCE | 3.0 |
| MEGN532 | EXPERIMENTAL METHODS IN BIOMECHANICS | 3.0 |
| MEGN535 | MODELING AND SIMULATION OF HUMAN MOVEMENT | 3.0 |
| MEGN536 | COMPUTATIONAL BIOMECHANICS | 3.0 |
| MTGN570 | BIOCOMPATIBILITY OF MATERIALS | 3.0 |
| MTGN572 | BIOMATERIALS | 3.0 |

## Mines' Combined Undergraduate / Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

**BIOL500. CELL BIOLOGY AND BIOCHEMISTRY. 4.0 Semester Hrs.**
This course will provide students with deep biological insight as well as hands-on experience of studying a biological question at the level of the cell, including gene expression and localization of proteins in eukaryotic cells, to the level of the protein, from molecular biology of the gene to characterization of posttranslational modifications, and protein purification and biochemical and biophysical characterization of protein structure and dynamics. These fundamental properties will be linked to protein activity and function. The emphasis of this course is on quantitative biology. Wherever appropriate, advanced concepts of protein chemistry and physics will be integrated into the delivery of the basic concepts. the course includes a 3 credit hour lecture section and a 1 credit hour PRACTICUM (instead of the lab) section.
**Course Learning Outcomes**

- Students will be familiar with basic terminology of all aspects of biology and will be able to recognize important cellular functions by their names
- Students will be able to define the chemical building blocks of biomolecules and understand how these connect to biological functions
- Students will be able to visualize protein and other molecular structures and their interactions using pymol software
- Students will have gained sufficient insight into different areas of biology and medicine to make informed decisions on their future career path
- Students will be able to make quantitative statements on the major biological processes
- Students will be familiar with modern –omics approaches and will know what can and what cannot be learned from them
- Students will be trained to identify opportunities for studying the interfaces between Mines' themes of earth, environment and energy and specific applications in biology and health
- Students will gain an appreciation of the benefits of integrating quantitative, computational approaches and design experimental approaches to test predictions
- Students will be able to analyze large datasets as a result of the sister course and derive biological hypotheses from them based on current understanding of biomolecules studied in this class
- Students will be able to critically evaluate existing bio/medical data and derive gaps in knowledge
- Students will be trained in active thinking and design of future work to address identified gaps

**BIOL501. ADVANCED BIOCHEMISTRY. 3.0 Semester Hrs.**
Advanced study of the major molecules of biochemistry: amino acids, proteins, enzymes, nucleic acids, lipids, and saccharides- their structure,

chemistry, biological function, biosynthesis, and interaction. Stresses bioenergetics and the cell as a biological unit of organization. Advanced discussion of the intertwining of molecular genetics, biomolecule synthesis, and metabolic cycles. Prerequisites: CHGN428 or BIOL500.
**Course Learning Outcomes**

- Demonstrate a broad knowledge of the fundamental introductory concepts of Chemistry, Biology and Physics
- Demonstrate a thorough knowledge of the intersection between the disciplines of Biology and Chemistry.
- Locate, critically analyze, interpret and discuss data, hypotheses, results, theories, and explanations found in the primary literature, applying knowledge from Chemistry and Biology.
- Appreciate the way in which practitioners in the disciplines of Biology and Chemistry intersect and bring their expertise to bear in solving complex problems involving living systems.

**BIOL510. BIOINFORMATICS. 3.0 Semester Hrs.**
Bioinformatics is a blend of multiple areas of study including biology, data science, mathematics and computer science. The field focuses on extracting new information from massive quantities of biological data and requires that scientists know the tools and methods for capturing, processing and analyzing large data sets. Bioinformatics scientists are tasked with performing high-throughput, next-generation sequencing. They analyze DNA sequence alignment to find mutations and anomalies and understand the impact on cellular processes. The bioinformatician uses software to analyze protein structure and its impact on cell function. Learning how to design experiments and perform advanced statistical analysis is essential for anyone interested in this field, which is main goal of this course. Prerequisite: CSCI102.
**Course Learning Outcomes**

- 1. knowledge and awareness of the basic principles and concepts of biology, computer science and mathematics;
- 2. existing software effectively to extract information from large databases and to use this information in computer modeling;
- 3. problem-solving skills, including the ability to develop new algorithms and analysis methods;
- 4. an understanding of the intersection of life and information sciences, the core of shared concepts, language and skills;
- 5. the ability to speak the language of structure-function relationships, information theory, gene expression, and database queries.

**BIOL520. SYSTEMS BIOLOGY. 3.0 Semester Hrs.**
This course provides students an introduction to the emerging field of systems biology. It will consist of lectures, group discussion sessions, and problem-solving sessions and/or computational labs. Students will learn strategies and tools to interrogate biological systems using mathematical modeling. Topics of the course will come from typical aspects of biomathematical modeling including, but not limited to: the choice of a modeling framework from various approaches; the design of interaction diagrams; the identification of variables and processes; the design of systems models; standard methods of parameter estimation; the analysis of steady states, stability, sensitivity; numerical evaluations of transients; phase-plane analysis; simulation of representative biological scenarios. All theoretical concepts are exemplified with applications.
**Course Learning Outcomes**

- At the completion of the course, students will be able to:1. Describe and understand important types of quantitative/mathematical models used in the field of systems biology
- 2. Explain the basic strengths and limitations of quantitative/mathematical modeling of biological systems
- 3. Design and implement quantitative/mathematical models of biological systems
- 4. Apply appropriate techniques for steady-state and dynamical analysis of models
- 5. Utilize different modeling tools for the analysis of models and their output
- 6. Assimilate current systems biology literature, extend it in a final project, and communicate results professionally and effectively

**BIOL590. QUANTITATIVE BIOSCIENCES & ENGINEERING GRADUATE SEMINAR. 1.0 Semester Hr.**
(I,II) The Quantitative Biosciences and Engineering (QBE) Graduate Seminar provides a forum for QBE graduate students to participate in seminars given by QBE professionals, develop an enhanced understanding of the breadth of quantitative bioscience disciplines, and present their research projects. Grade is based on attendance over the semester. Full-time graduate students must enroll in the Graduate Seminar course every semester that they are enrolled at Mines. Repeatable; maximum 2 credits granted towards MS degree requirements and 4 credits maximum granted towards PhD Requirements.

**BIOL707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.**
(I, II, S) Research credit hours required for completion of a Masters-level thesis or Doctoral dissertation. Research must be carried out under the direct supervision of the student's faculty advisor. Variable class and semester hours. Repeatable for credit.

## Advising Faculty

Joel Bach, Associate Professor of Mechanical Engineering

Cecilia Diniz Behn, Associate Professor of Applied Mathematics & Statistics

Nanette Boyle, Associate Professor of Chemical and Biological Engineering

Kevin Cash, Assistant Professor of Chemical and Biological Engineering

Anuj Chauhan, Professor of Chemical and Biological Engineering

Dylan Domaille, Assistant Professor of Chemistry

Christopher Higgins, Professor of Civil and Environmental Engineering

Melissa Krebs, Co-Director, QBE Graduate Program and Associate Professor of Chemical and Biological Engineering

Ramya Kumar, Assistant Professor of Chemical and Biological Engineering

Karin Leiderman, Co-Director, QBE Graduate Program and Associate Professor of Applied Mathematics & Statistics

Terry Lowe, Research Professor of Materials and Metallurgical Engineering

David Marr, Professor of Chemical and Biological Engineering

Alexander Pak, Assistant Professor, Chemical and Biological Engineering

Steve Pankavich, Associate Professor of Applied Mathematics & Statistics

Anthony Petrella, Associate Professor of Mechanical Engineering

Andrew Petruska, Assistant Professor of Mechanical Engineering

Matthew Posewitz, Professor of Chemistry

James Ranville, Professor of Chemistry

Jonathan Sharp, Associate Professor of Civil and Environmental Engineering

Anne Silverman, Associate Professor of Mechanical Engineering

E. Dendy Sloan, Emeritus Professor of Chemical and Biological Engineering

John Spear, Professor, Civil and Environmental Engineering

Jeff Squier, Professor of Physics

Amadeu Sum, Professor of Chemical and Biological Engineering

Brian Trewyn, Associate Professor of Chemistry

Shubham Vyas, Associate Professor of Chemistry

Hua Wang, Associate Professor of Computer Science

Xiaoli Zhang, Associate Professor of Mechanical Engineering

## Teaching Faculty

Linda Battalora, Teaching Professor of Petroleum Engineering

Suzannah Beeler, Assistant Teaching Professor of Chemical and Biological Engineering

Christian Beren, Teaching Assistant Professor of Chemistry

Kristine Csavina, Teaching Professor of Mechanical Engineering

Duncan Davis-Hall, Teaching Assistant Professor of Engineering, Design, & Society

Alina Handorean, Teaching Professor of Engineering, Design & Society

Josh Ramey, Director of the QBE Undergraduate Program and Teaching Associate Professor of Chemical and Biological Engineering

Justin Shaffer, Teaching Associate Professor of Chemical and Biological Engineering

# Quantum Engineering

Degrees Offered

- Graduate certificate in Quantum Engineering
- Master of Science (non-thesis)
- Master of Science (thesis)

## Program Requirements

Quantum Engineering is an interdisciplinary program that seeks to equip students for careers in  emerging technologies based on quantum entanglement. It encompasses a wide range of disciplines that include physics, materials science, computer science, and mathematics, and is necessarily a collaborative effort among many Mines departments.  Two master's degrees and one graduate certificate are offered.

For both degrees and the graduate certificate, Quantum Engineering has two "tracks" as summarized below. The Quantum Engineering Hardware (QEH) track will focus on experimental techniques relevant to quantum technology, while the Quantum Engineering Software (QES) track will focus on theory, algorithms and simulation. Students must choose a track to complete the program, but they may take courses from both tracks provided they meet the prerequisite requirements.

## MS Degree Curriculum Requirements:

A Master of Science in Quantum Engineering will consist of 30 total credits. Students may choose a thesis or non-thesis option for this degree. For the thesis option, 9 credits out of the 30 are devoted to thesis research leading to an acceptable Master's thesis. Students choosing the non-thesis option will devote all 30 credits to coursework. Regardless of the option chosen, 9 of the coursework credits will be devoted to the required core classes for the chosen track.

Reflecting the interdisciplinary nature of the program, we strongly recommend to our students that at least 9 total credits of the MS degree coursework should come from courses in a department outside of the student's undergraduate major. The required core courses, if outside of the student's major, would count toward this recommendation. Our guiding philosophy is that the problem of building a quantum computer is a complex, interdisciplinary one which requires contributions from a vast array of subfields, and young scientists who appreciate this will likely have a far better perspective on the field than those who do not.

## MS Non-Thesis Software Track

| | | |
|---|---|---|
| PHGN519 | FUNDAMENTALS OF QUANTUM INFORMATION | 3.0 |
| CSCI581 | QUANTUM PROGRAMMING | 3.0 |
| PHGN545 | QUANTUM MANY-BODY PHYSICS | 3.0 |
| PHGN526 | QUANTUM ENGINEERING SEMINAR (FALL) | 1.0 |
| PHGN527 | QUANTUM ENGINEERING SEMINAR (SPRING) | 1.0 |
| Electives | | 19.0 |
| **Total Semester Hrs** | | **30.0** |

## MS Non-Thesis Hardware Track

| | | |
|---|---|---|
| PHGN519 | FUNDAMENTALS OF QUANTUM INFORMATION | 3.0 |
| EENG532 | LOW TEMPERATURE MICROWAVE MEASUREMENTS FOR QUANTUM ENGINEERING | 3.0 |
| PHGN535 | INTERDISCIPLINARY SILICON PROCESSING LABORATORY | 3.0 |
| PHGN526 | QUANTUM ENGINEERING SEMINAR (FALL) | 1.0 |
| PHGN527 | QUANTUM ENGINEERING SEMINAR (SPRING) | 1.0 |
| Electives | | 19.0 |
| **Total Semester Hrs** | | **30.0** |

## MS Thesis Software Track

| | | |
|---|---|---|
| PHGN519 | FUNDAMENTALS OF QUANTUM INFORMATION | 3.0 |
| CSCI581 | QUANTUM PROGRAMMING | 3.0 |
| PHGN545 | QUANTUM MANY-BODY PHYSICS | 3.0 |
| PHGN526 | QUANTUM ENGINEERING SEMINAR (FALL) | 1.0 |

| | | |
|---|---|---|
| PHGN527 | QUANTUM ENGINEERING SEMINAR (SPRING) | 1.0 |
| Electives | | 9.0 |
| PHGN707 | GRADUATE THESIS / DISSERTATION RESEARCH CREDIT | 10.0 |
| **Total Semester Hrs** | | **30.0** |

## MS Thesis Hardware Track

| | | |
|---|---|---|
| PHGN519 | FUNDAMENTALS OF QUANTUM INFORMATION | 3.0 |
| EENG/PHGN532 | LOW TEMPERATURE MICROWAVE MEASUREMENTS FOR QUANTUM ENGINEERING | 3.0 |
| PHGN535 | INTERDISCIPLINARY SILICON PROCESSING LABORATORY | 3.0 |
| PHGN526 | QUANTUM ENGINEERING SEMINAR (FALL) | 1.0 |
| PHGN527 | QUANTUM ENGINEERING SEMINAR (SPRING) | 1.0 |
| Electives | | 9.0 |
| PHGN707 | GRADUATE THESIS / DISSERTATION RESEARCH CREDIT | 10.0 |
| **Total Semester Hrs** | | **30.0** |

## Coursework Details:

QES students will be required to take these courses in the following sequence:

In the fall:

- PHGN519, Fundamentals of Quantum Information

In the spring:

- CSCI581, Quantum Programming
- PHGN545, Quantum Many-Body Physics

QEH students will be required to take these courses in the following sequence:

In the fall:

- PHGN519, Fundamentals of Quantum Information

In the spring:

- PHGN535, Interdisciplinary Silicon Processing Laboratory
- PHGN532, Low Temperature Microwave Measurements for Quantum Applications

## Approved Electives:

| | | |
|---|---|---|
| **Physics Electives** | | |
| PHGN511 | MATHEMATICAL PHYSICS | 3.0 |
| PHGN520 | QUANTUM MECHANICS I | 3.0 |
| PHGN521 | QUANTUM MECHANICS II | 3.0 |
| PHGN530 | STATISTICAL MECHANICS | 3.0 |
| PHGN550 | NANOSCALE PHYSICS AND TECHNOLOGY | 3.0 |
| PHGN566 | MODERN OPTICAL ENGINEERING | 3.0 |
| PHGN581 | LASER PHYSICS | 3.0 |
| PHGN585 | NONLINEAR OPTICS | 3.0 |
| **Computer Science Electives** | | |
| CSCI542 | SIMULATION | 3.0 |
| CSCI561 | THEORY OF COMPUTATION | 3.0 |
| CSCI563 | PARALLEL COMPUTING FOR SCIENTISTS AND ENGINEERS | 3.0 |
| CSCI564 | ADVANCED COMPUTER ARCHITECTURE | 3.0 |
| CSCI571 | ARTIFICIAL INTELLIGENCE | 3.0 |
| CSCI575 | ADVANCED MACHINE LEARNING | 3.0 |
| CSCI574 | THEORY OF CRYPTOGRAPHY | 3.0 |
| CSCI580 | ADVANCED HIGH PERFORMANCE COMPUTING | 3.0 |
| **Electrical Engineering Electives** | | |
| EENG509 | SPARSE SIGNAL PROCESSING | 3.0 |
| EENG517 | THEORY AND DESIGN OF ADVANCED CONTROL SYSTEMS | 3.0 |
| EENG526 | ADVANCED ELECTROMAGNETICS | |
| EENG528 | COMPUTATIONAL ELECTROMAGNETICS | |
| EENG529 | ACTIVE RF & MICROWAVE DEVICES | |
| EENG530 | PASSIVE RF & MICROWAVE DEVICES | 3.0 |
| EENG617 | INTELLIGENT CONTROL SYSTEMS | 3.0 |
| EENG618 | NONLINEAR AND ADAPTIVE CONTROL | 3.0 |
| **Metallurgy and Material Engineering Electives** | | |
| **Materials Science Electives** | | |
| MTGN605 | ADVANCED TRANSMISSION ELECTRON MICROSCOPY | 2.0 |
| MTGN605L | ADVANCED TRANSMISSION ELECTRON MICROSCOPY LABORATORY | 1.0 |
| MTGN656 | ADVANCED ELECTRON MICROSCOPY | 2.0 |
| MTGN656L | ADVANCED ELECTRON MICROSCOPY LABORATORY | 1.0 |
| MLGN502 | SOLID STATE PHYSICS | 3.0 |
| MTGN573 | COMPUTATIONAL MATERIALS | 3.0 |
| MLGN515 | ELECTRICAL PROPERTIES AND APPLICATIONS OF MATERIALS | 3.0 |
| MLGN583 | PRINCIPLES AND APPLICATIONS OF SURFACE ANALYSIS TECHNIQUES | 3.0 |
| MLGN593 | BONDING, STRUCTURE, AND CRYSTALLOGRAPHY | 3.0 |
| **Applied Mathematics and Statistics Electives** | | |
| MATH506 | COMPLEX ANALYSIS II | 3.0 |
| MATH510 | ORDINARY DIFFERENTIAL EQUATIONS AND DYNAMICAL SYSTEMS | 3.0 |
| MATH536 | ADVANCED STATISTICAL MODELING | 3.0 |
| MATH538 | STOCHASTIC MODELS | 3.0 |
| MATH550 | NUMERICAL SOLUTION OF PARTIAL DIFFERENTIAL EQUATIONS | 3.0 |
| MATH551 | COMPUTATIONAL LINEAR ALGEBRA | 3.0 |
| **Humanities, Arts, and Social Sciences Electives** | | |
| HASS523 | ADVANCED SCIENCE COMMUNICATION | 3.0 |

## Mines' Combined Undergraduate/Graduate Degree Program:

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be

substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

## Graduate Certificate Curriculum Requirements:

The certificate option consists of three of the four new courses, plus one additional elective chosen from the above list, for a total of 12 credits.

### Graduate Certificate, Software Track

| | | |
|---|---|---|
| PHGN519 | FUNDAMENTALS OF QUANTUM INFORMATION | 3.0 |
| CSCI581 | QUANTUM PROGRAMMING | 3.0 |
| PHGN545 | QUANTUM MANY-BODY PHYSICS | 3.0 |
| Elective | | 3.0 |
| **Total Semester Hrs** | | **12.0** |

### Graduate Certificate, Hardware Track

| | | |
|---|---|---|
| PHGN519 | FUNDAMENTALS OF QUANTUM INFORMATION | 3.0 |
| PHGN535 | INTERDISCIPLINARY SILICON PROCESSING LABORATORY | 3.0 |
| EENG/PHGN532 | LOW TEMPERATURE MICROWAVE MEASUREMENTS FOR QUANTUM ENGINEERING | 3.0 |
| Elective | | 3.0 |
| **Total Semester Hrs** | | **12.0** |

## Program Director

Meenakshi Singh, Associate Professor, Physics

## Department of Chemical and Biological Engineering

Matthew Crane, Assistant Professor

## Department of Computer Science

Neil Dantam, Assistant Professor

Dinesh Mehta, Professor

Bo Wu, Associate Professor

Dejun Yang, Associate Professor

## Department of Electrical Engineering

Peter Aaen, Professor

## Department of Metallurgical and Materials Engineering

Geoff Brennecka, Professor

Brian Gorman, Professor

## Department of Physics

Victoria Borish, Teaching Assistant Professor

Lincoln Carr, Professor

Patrice Genevet, Professor

Zhexuan Gong, Assistant Professor

Eliot Kapit, Associate Professor

Kyle Leach, Associate Professor

Wouter Van De Pontseele, Assistant Professor

Frederic Sarazin, Professor

Jeff Squier, Professor

## Affiliated Faculty

Matt Beard, Joint Appointment, NREL and Chemistry

Justin Johnson, NREL

Andriy Zakutayev, Joint Appointment, NREL and Metallurgical and Materials Engineering

# Robotics

## Degrees Offered

- Graduate certificate in Robotics
- Master of Science in Robotics (non-thesis)
- Master of Science in Robotics (thesis)
- Doctor of Philosophy in Robotics

The Robotics program offers graduate certificate, Master of Science and Doctor of Philosophy degrees in Robotics. The graduate certificate is intended for working professionals. The non-thesis MS is designed to prepare candidates for industry careers in robotics. The thesis MS and PhD degrees are designed to prepare students for research careers.

## Program Director

Andrew Petruska

## Professors

Qi Han

Tyrone Vincent

Kevin Moore

## Associate Professors

Kathryn Johnson

Hao Zhang

Xiaoli Zhang

## Assistant Professors

Neil Dantam

Andrew Petruska

Thomas Williams

Qin Zhu

The Robotics program offers graduate certificate, Master of Science and Doctor of Philosophy degrees in Robotics. The graduate certificate is intended for working professionals. The non-thesis MS is designed to prepare candidates for industry careers in robotics. The thesis MS and PhD degrees are designed to prepare students for research careers.

Combined Program: The Robotics program also offers combined BS+MS degrees. These degrees offer an expedited graduate school application process and allow students to begin graduate coursework while still finishing their undergraduate degree requirements.

# Admissions and Program Policies

## Mines' Combined Undergraduate/Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

## MS and PhD

The minimum requirements for admission to the MS and PhD degrees in Robotics are:

• Applicants must have a Bachelor's degree, or equivalent, from an accredited institution with a grade-point average of 3.0 or better on a 4.0 scale prior to matriculating into the Robotics degree program.

• Students are expected to have completed the following coursework: 1) two semesters of calculus, 2) differential equations, and 3) data structures. The Robotics graduate admissions committee may require that students who do not meet this expectation demonstrate competency or take remedial coursework. Such coursework may not count toward the graduate degree. The committee will decide whether to recommend regular or provisional admission.

• Graduate Record Examination (Quantitative section) score of 151 or higher (or 650 on the old scale). Applicants who have graduated with a computer science, engineering, or math degree from Mines within the past five years are not required to submit GRE scores.

• Applicants who are not U.S. citizens or permanent residents and whose native language is not English, must prove English proficiency as part of the application process. Refer to the Graduate Admissions website for more details.

• For the PhD program, prior research experience is desired but not required.

## Transfer Credit

Graduate-level courses taken at other universities for which a grade equivalent to a B or better was received will be considered for transfer credit with approval of the advisor and/or thesis committee, and home department head, as appropriate. Transfer credits must not have been used as credit toward a bachelor's degree. For the MS degree, no more than nine credits may transfer. For the PhD degree, up to 24 credits of courses may be transferred. In lieu of transfer credit for individual courses, students who enter the PhD program with a thesis-based master's degree from another institution may transfer up to 36 credits in recognition of the course work and research completed for that degree.

## Advisor and Thesis Committees

Students must have an advisor from the Robotics faculty to direct and monitor their academic plan, research, and independent studies. Advisors must be full-time permanent members of the faculty. In this context, full-time permanent members of the faculty are those that hold the rank of professor, associate professor, assistant professor, research professor, associate research professor or assistant research professor. Upon approval by the graduate dean, adjunct faculty, teaching faculty, visiting professors, emeritus professors and off-campus representatives may be designated additional co-advisors. A list of Robotics faculty by rank is available in the faculty tab of the catalog.

The department of the advisor is the student's home department.

Master of Science (thesis option) students in Robotics must have at least three members on their thesis committee. In addition to the institutional requirements, at least one committee member who is not the advisor must be Robotics faculty.

Robotics PhD thesis committees must have at least four members. In addition to the institutional requirements, at least one committee member who is not the advisor must be Robotics faculty.

# Program Requirements

## Graduate Certificate

The graduate certificate will require 12 credits of coursework. The table below summarizes the requirements for the graduate certificate.

| | | |
|---|---|---|
| Robotics Core | Four courses, one from each focus area's core course list | 12.0 |
| **Total Semester Hrs** | | **12.0** |

## MS Degrees

The MS degrees will require 30 credits, with thesis research options substituting for electives.

### MS Non-Thesis (MS-NT)

Students must take 30 credits of coursework to complete the degree. The table below summarizes the requirements for the MS-NT degree.

| | | |
|---|---|---|
| Robotics Core (Breadth) | Four courses, one from each focus area's core course list | 12.0 |
| Robotics Electives (Depth) | Two courses from robotics course list | 6.0 |
| Technical Electives | Four courses in any participating robotics department (CSCI, EDNS, EENG, MATH, MEGN) | 12.0 |
| **Total Semester Hrs** | | **30.0** |

## MS Thesis

Students must take 21 credits of coursework and 9 credits of MS thesis research to complete the degree. The table below summarizes the requirements for the MS Thesis degree.

At the conclusion of the MS thesis, the student must make a formal presentation and defense of their thesis research. A student must pass this defense to earn an MS degree.

| | | |
|---|---|---|
| Robotics Core (Breadth) | Four courses, one from each focus area's core course list | 12.0 |
| Robotics Electives (Depth) | Two courses from robotics course list | 6.0 |
| Technical Electives | One course in any participating robotics department (CSCI, EDNS, EENG, MATH, MEGN) | 3.0 |
| MEGN707 | GRADUATE THESIS / DISSERTATION RESEARCH CREDIT | 9.0 |
| **Total Semester Hrs** | | **30.0** |

## PhD Degree

The Robotics PhD requires 36 credits of coursework plus 36 research credits. The table below summarizes the coursework requirements. PhD students must additionally complete a qualifying examination, a thesis proposal, and a thesis defense.

| | | |
|---|---|---|
| Robotics Core (Breadth) | Four courses, one from each focus area's core course list | 12.0 |
| Robotics Electives (Depth) | Four Courses from robotics course list | 12.0 |
| Technical Electives | Four courses in any participating robotics department (CSCI, EDNS, EENG, MATH, MEGN) | 12.0 |
| MEGN707 | GRADUATE THESIS / DISSERTATION RESEARCH CREDIT | 36.0 |
| **Total Semester Hrs** | | **72.0** |

## Robotics PhD Qualifying Examination

The Robotics PhD Qualifying Examination will test a student's ability to conduct research in their chosen area. The qualifier will have two components: a coursework component and a research component.

**Coursework Qualifier:** To satisfy the coursework component of the qualifier, the student must complete their four selected Robotics core courses with a minimum grade of B in each class.

**Research Qualifier:** The research qualifier consists of a research project. Robotics PhD students must take the qualifying examination by the end of their fourth semester (typically by the end of their second year). The examination will be evaluated by a committee consisting of at least the student's advisor, a Robotics-affiliated faculty member, and one additional faculty member.

For the qualifier, the student will conduct a literature review of 30-40 papers and perform a research project approaching the level necessary for a conference publication. The research project must be approved by the advisor and committee and will likely be some combination of the following:

- Design, analyze and/or simulate a novel robot system,
- Design and evaluate new algorithms or systems for an important research problem,
- Develop a new research software system,
- Solve a set of theoretical problems.

The deliverables will be a literature review (3-4 pages, IEEE style [4]), a research report (4-5 pages, IEEE style), and a research presentation (30 minutes to present, plus questions) delivered to the committee.

At the conclusion of the qualifier presentation, each committee member will vote their evaluation as one of "Strong Support," "Weak Support," or "Do not support." The student must receive at least two "Strong Support" votes to pass. In the case the student does not pass, the committee may decide to offer a "conditional pass" based on extra conditions, such as revisions to the report or additional experiments, the student must perform to pass the qualifier. The committee will set an explicit deadline for student to complete the extra conditions. If the student does not meet the extra conditions as determined by the committee by the deadline, the "conditional pass" becomes a "fail." If the student does not pass the qualifier on their first attempt (inclusive of a conditional pass), they may make one additional attempt to pass; the same conditional pass procedure may also be applied to the second attempt. A student who fails the qualifier on the second attempt may not continue in the program.

## Robotics PhD Proposal and Defense

After passing the qualifying examination, the student must prepare a written thesis proposal and present it formally to the student's thesis committee and other interested faculty. Typically, the proposal will take place within 24 months of the student completing the qualifier.

The committee for the thesis proposal and defense will follow institutional requirements. Additionally, at least one committee member who is not the advisor must be robotics-affiliated faculty.

At the conclusion of the student's PhD program, the student must make a formal presentation and defense of their thesis research. A student must "pass" this defense to earn a PhD degree. Typically, the defense will take place within 24 months of the student completing the thesis proposal.

## Robotics Course List

The Robotics courses are divided into four focus areas. Each focus area is comprised of core courses and electives, as detailed below. Beyond the courses in these four focus areas, there is also a list of additional Robotics electives.

Perception

**Core Courses**

| | | |
|---|---|---|
| ROBO513 | ROBOT PROGRAMMING AND PERCEPTION | 3.0 |
| ROBO517 | INTRODUCTION TO COMPUTER VISION | 3.0 |
| ROBO529 | ESTIMATION THEORY AND KALMAN FILTERING | 3.0 |

**Elective Courses**

| | | |
|---|---|---|
| CSCI508 | ADVANCED TOPICS IN PERCEPTION AND COMPUTER VISION | 3.0 |

Cognition

**Core Courses**

| | | |
|---|---|---|
| ROBO534 | ROBOT PLANNING AND MANIPULATION | 3.0 |
| ROBO535 | ADVANCED MACHINE LEARNING | 3.0 |

**Elective Courses -** None.

Action

**Core Courses**

| | | |
|---|---|---|
| ROBO554 | ROBOT MECHANICS: KINEMATICS, DYNAMICS, AND CONTROL | 3.0 |
| ROBO550 | MECHATRONICS | 3.0 |
| ROBO565 | ADVANCED ROBOT CONTROL | 3.0 |
| ROBO567 | THEORY AND DESIGN OF ADVANCED CONTROL SYSTEMS | 3.0 |

**Elective Courses**

| | | |
|---|---|---|
| EENG515 | MATHEMATICAL METHODS FOR SIGNALS AND SYSTEMS | 3.0 |

Interaction & Society

**Core Courses**

| | | |
|---|---|---|
| ROBO572 | ROBOT ETHICS | 3.0 |
| ROBO576 | HUMAN-ROBOT INTERACTION | 3.0 |

**Elective Courses**

| | | |
|---|---|---|
| CSCI5XX | LINGUISTIC HUMAN-ROBOT INTERACTION | 3.0 |

Additional Robotics Electives

| | | |
|---|---|---|
| CSCI561 | THEORY OF COMPUTATION | 3.0 |
| CSCI562 | APPLIED ALGORITHMS AND DATA STRUCTURES | 3.0 |
| CSCI565 | DISTRIBUTED SYSTEMS | 3.0 |
| CSCI572 | COMPUTER NETWORKS II | 3.0 |
| EENG511 | CONVEX OPTIMIZATION AND ITS ENGINEERING APPLICATIONS | 3.0 |
| EENG521 | NUMERICAL OPTIMIZATION | 3.0 |
| MEGN586 | LINEAR OPTIMIZATION | 3.0 |
| MEGN587 | NONLINEAR OPTIMIZATION | 3.0 |
| MEGN588 | INTEGER OPTIMIZATION | 3.0 |
| MEGN686 | ADVANCED LINEAR OPTIMIZATION | 3.0 |
| MEGN688 | ADVANCED INTEGER OPTIMIZATION | 3.0 |

**ROBO513. ROBOT PROGRAMMING AND PERCEPTION. 3.0 Semester Hrs.**
In this class students will learn the basics of integrated robot system programming and the design and use of algorithms for robot perception. Students will learn how to use the ROS robot middleware for the design of robot systems for perceiving and navigating the world; develop reinforcement learning based models for perception-informed autonomous navigation; and develop computational models for 3D robot perception and perceptual representation of human data.
**Course Learning Outcomes**

- 1. Explain the basic concepts in human-centered robotics
- 2. Model and analyze human behaviors for human-robot interaction applications
- 3. Recognize the cutting-edge human-centered robotics research and applications
- 4. Apply the learned knowledge to other fields

**ROBO517. INTRODUCTION TO COMPUTER VISION. 3.0 Semester Hrs.**
(I) Computer vision is the process of using computers to acquire images, transform images, and extract symbolic descriptions from images. This course provides an introduction to this field, covering topics in image formation, feature extraction, location estimation, and object recognition. Design ability and hands-on projects will be emphasized, using popular software tools. The course will be of interest both to those who want to learn more about the subject and to those who just want to use computer imaging techniques. 3 hours lecture; 3 semester hours. Prerequisite: Undergraduate level knowledge of linear algebra, statistics, and a programming language.
**Course Learning Outcomes**

- 1. Be able to analyze and predict the behavior of image formation, transformation, and recognition algorithms
- 2. Be able to design, develop, and evaluate algorithms for specific applications
- 3. Be able to use software tools to implement computer vision algorithms
- 4. Communicate (in oral and written form) methods and results to a technical audience

**ROBO529. ESTIMATION THEORY AND KALMAN FILTERING. 3.0 Semester Hrs.**
Estimation theory considers the extraction of useful information from raw sensor measurements in the presence of signal uncertainty. Common applications include navigation, localization and mapping, but applications can be found in all fields where measurements are used. Mathematic descriptions of random signals and the response of linear systems are presented. The discrete-time Kalman Filter is introduced, and conditions for optimality are described. Implementation issues, performance prediction, and filter divergence are discussed. Adaptive estimation and nonlinear estimation are also covered. Contemporary applications will be utilized throughout the course. Offered Spring semester of odd years. 1.5 hours lecture; 1.5 hours other; 3 semester hours.
**Course Learning Outcomes**

- Use Bayes' rule to calculate a statistical inference. Given a description of a stochastic process, calculate the joint and conditional probabilities for this process.
- Using the appropriate algorithm, calculate the probability distribution function for the state of a dynamic system with stochastic inputs.
- " Build a model of a dynamic system that includes a probabilistic description of uncertain inputs.
- Design and implement an algorithm to estimate the internal states of a linear system with input signals that are Gaussian stochastic processes.
- Design and implement an algorithm to estimate the internal states of general systems with general stochastic inputs.

**ROBO534. ROBOT PLANNING AND MANIPULATION. 3.0 Semester Hrs.**
An introduction to planning in the context of robotics covering symbolic and motion planning approaches. Symbolic computation, symbolic domains, and efficient algorithms for symbolic planning; Robot kinematics, configuration spaces, and algorithms for motion planning. Applications of planning will focus on manipulation problems using robot arms.
**Course Learning Outcomes**

- 1 - Implement algorithms for symbolic computation
- 2 - Construct symbolic planning domains for new scenarios
- 3 - Implement algorithms for symbolic planning via constraint-solving and heuristic search
- 4 - Implement algorithms for sampling-based motion planning
- 5 - Construct kinematic models of robot manipulators
- 6 - Analyze planning algorithms for key properties: correctness, completeness, optimality
- 7 - Evaluate the suitability of different planning approaches and apply appropriate algorithms to new planning scenarios
- 8 - Communicate implementations, analysis, and evaluation in written and oral form

**ROBO535. ADVANCED MACHINE LEARNING. 3.0 Semester Hrs.**
Machine learning is the study of computer algorithms that improve automatically through experience. Machine learning systems do not have to be programmed by humans to solve a problem; instead, they essentially program themselves based on examples of how they should behave, or based on trial and error experience trying to solve the problem. This course aims at provide students with an understanding of the capabilities of machine learning (especially for deep learning due to its state-of-the-art performance for predicting and understanding data), and the knowledge to formulate the real-world problem to solve it effectively by a combination of computational idea motivations, learning theories, mathematical and optimization backgrounds/tools.

**ROBO550. MECHATRONICS. 3.0 Semester Hrs.**
A course focusing on implementation aspects of mechatronic and control systems. Significant lab component involving embedded C programming on a mechatronics teaching platform, called a haptic paddle, a single degree-of-freedom force-feedback joystick.
**Course Learning Outcomes**

- 1. Become proficient in mechanical system modeling, system identification and simulations.
- 2. Develop an understanding of how control theory is applied and implemented in practice.
- 3. Learn fundamentals of and how to use semiconductor devices in mechatronic systems
- 4. Learn the basics of sensor and actuator theory, design, and application
- 5. Gain experience in embedded C programming for mechatronic systems
- 6. Gain experience in research article reading and technical presentations

**ROBO554. ROBOT MECHANICS: KINEMATICS, DYNAMICS, AND CONTROL. 3.0 Semester Hrs.**
Mathematical representation of robot structures. Mechanical analysis including kinematics, dynamics, and design of robot manipulators. Representations for trajectories and path planning for robots. Fundamentals of robot control including, linear, nonlinear and force control methods. Introduction to off-line programming techniques and simulation. 3 hours lecture; 3 semester hours. Prerequisites: EENG307 and MEGN441.

**ROBO565. ADVANCED ROBOT CONTROL. 3.0 Semester Hrs.**
The goal of this course is to give the students an introduction to a fundamental working knowledge of the main techniques of intelligent learning-based control and their applications in robotics and autonomous systems. Specific topics include neural network based control, model predictive control, reinforcement learning based control, fuzzy logic control, and human-in-the-loop control.

**ROBO567. THEORY AND DESIGN OF ADVANCED CONTROL SYSTEMS. 3.0 Semester Hrs.**
This course will introduce and study the theory and design of multivariable and nonlinear control systems. Students will learn to design multivariable controllers that are both optimal and robust, using tools such as state space and transfer matrix models, nonlinear analysis, optimal estimator and controller design, and multi-loop controller synthesis. Offered Spring semester of even years. Prerequisite: EENG417.
**Course Learning Outcomes**

- 1. define control-oriented problem statements for real-world problems,
- 2. model, analyze, and design controllers and estimators for single-input, single-output (SISO) and multi-input, multi-output (MIMO) systems in time and frequency domains,
- 3. design optimal and robust controllers and estimators for these systems,
- 4. model, analyze, and design controllers for nonlinear systems,
- 5. explain the connection between state-space and transfer function representations of systems and the effects on controller design and analysis
- 6. model, analyze, and design feedback control systems using MATLAB and Simulink in both the time and frequency domains, and
- 7. understand and apply basic educational and learning theories and tools that will enhance your lifelong learning.

**ROBO572. ROBOT ETHICS. 3.0 Semester Hrs.**
(II) This course explores ethical issues arising in robotics and human-robot interaction through philosophical analysis, scientific experimentation, and algorithm design. Topics include case studies in lethal autonomous weapon systems, autonomous cars, and social robots, as well as higher-level concerns including economics, law, policy, and discrimination. Graduate enrollees will additionally participate in and report on the results of empirical and computational robot ethics research, with the goal of developing publishable works.
**Course Learning Outcomes**

- 1 - Understand the basic ethical theories, concepts, tools, and frameworks for analyzing the social and ethical ramifications of robotics
- 2 - Be able to critically examine the ethical significance of the use of robotics in daily and technical fields including human-robot interaction, medicine, relationship, military, etc.
- 3 - Develop a critical attitude toward the role of robotics in shaping human society including human perceptions and behaviors
- 4 - Be able to use the theories, concepts, tools, and frameworks learned from this class to critically examine emerging robot ethics issues in the society.

- 5 - Understand the tradeoffs underlying the design of autonomous moral agents.
- 6 - Conduct robot ethics research grounded in both human-subject experimentation and algorithm development.

**ROBO576. HUMAN-ROBOT INTERACTION. 3.0 Semester Hrs.**
Human-Robot Interaction is an interdisciplinary field at the intersection of Computer Science, Robotics, Psychology, and Human Factors, that seeks to answer a broad set of questions about robots designed to interact with humans (e.g., assistive robots, educational robots, and service robots), such as: (1) How does human interaction with robots differ from interaction with other people? (2) How does the appearance and behavior of a robot change how humans perceive, trust, and interact with that robot? And (3) How can we design and program robots that are natural, trustworthy, and effective? Accordingly, In this course, students will learn (1) how to design interactive robots, (2) the algorithmic foundations of interactive robots; and (3) how to evaluate interactive robots. To achieve these learning objectives, students will read and present key papers from the HRI literature, complete an individual final project tailored to their unique interests and skillsets, and complete a group project in which they will design, pilot, and evaluate novel HRI experiments, with in-class time expected to be split between lecture by the instructor, presentations by students, and either collaborative active learning activities or discussions with researchers in the field Prerequisite: Data Structures, Probability and Statistics or equivalent.
**Course Learning Outcomes**

- Understand the theoretical foundations and critical application domains of human-robot interaction.
- Employ design techniques to design interactive robots.
- Design human-subject experiments to evaluate interactive robots.
- Perform qualitative and quantitative analysis on the results of human-robot interaction experiments.

**ROBO598. SPECIAL TOPICS. 0-3 Semester Hr.**

**ROBO599. INDEPENDENT STUDY. 0.5-6 Semester Hr.**
Individual research or special problem projects supervised by a faculty member, also, when a student and instructor agree on a subject matter, content, and credit hours. Variable credit: 0.5 to 6 credit hours. Repeatable for credit under different topics/experience and maximums vary by department. Contact the Department for credit limits toward the degree.

**ROBO599. INDEPENDENT STUDY. 1-6 Semester Hr.**

**ROBO707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.**
Research credit hours required for completion of a Masters-level thesis or Doctoral dissertation. Research must be carried out under the direct supervision of the student's faculty advisor. Variable class and semester hours. Repeatable for credit.

# Space Resources

## Degrees Offered

- Graduate Certificate in Space Resources – online
- Master of Science in Space Resources (non-thesis) – online
- Doctor of Philosophy in Space Resources – on campus and online

## Program Description

Since the 1990s, Colorado School of Mines has been a leading institution for the study of space resources and their utilization through its *Center for Space Resources*. It has also become a destination for space scientists and engineers, government agencies, aerospace companies, entrepreneurs, the mining and minerals industry, financial and legal experts, and policy makers to discuss all topics related to this field at its annual *Space Resources Roundtable*.

In recent years, growing interest in the identification, extraction, and utilization of space resources by space agencies and the private sector has been driven by an awareness that further exploration and growth of commercial opportunities in space will require extraction of materials, production of propellants, and power generation from extraterrestrial resources for more affordable and flexible transportation, facilities construction, energy production, manufacturing of parts, and life support. The broad topic of space resources brings together many fields in which Mines has a strong presence, including remote sensing, geomechanics, mining, materials/metallurgy, robotics/automation, advanced manufacturing and construction, electrochemistry, solar and nuclear energy, resource economics, and public policy.

In this light, Mines launched a first-of-its-kind multi-disciplinary graduate program in Space Resources in 2017 to offer Post-Baccalaureate Certificate, Master of Science, and Ph.D. degrees for college graduates and professionals interested in this emerging arena. The program focuses on developing core knowledge and gaining design practices in systems for responsible exploration, extraction, use, and stewardship of resources in the Solar System.

## Contact

For more information, please check the Space Resources Program website: https://space.mines.edu, or contact the Director of the Program, Angel Abbud-Madrid (aabbudma@mines.edu).

## Space Resources Program Requirements

The interdisciplinary Space Resources program is targeted to train recent graduates, as well as professionals interested in expanding their knowledge and skills to address the opportunities and challenges in space resource exploration, extraction, and utilization. Space Resources touches on physical sciences, engineering, and the social science fields. Thus, this program engages faculty members from many academic departments at Mines. Graduates from the Space Resources program will be prepared to serve the growing interest of industry, government, and academia to identify, extract, process, and utilize resources beyond Earth. Students will have a broad, multi-disciplinary understanding of the overall flow of activities in the development of extraterrestrial resources, a high-level exposure to the different science, engineering, economics, and business disciplines involved in each phase, and an understanding of the current status in the space resources field across academia, government, and the private sector.

The graduate program for Space Resources includes the following degree options:

- a 12-credit-hour graduate certificate offered online,
- a 31-credit Master of Science Non-Thesis (MS-NT) degree in Space Resources offered online,
- a PhD program in Space Resources requiring a total of 72 credits of combined coursework and research, and a doctoral dissertation. The PhD program can be completed on campus and also online for those

students approved to conduct their research remotely by their advisor and dissertation committee.

## Mines' Combined Undergraduate/Graduate Degree Program

With approval of the Space Resources Program faculty, students may be allowed to enroll in a combined undergraduate/graduate program in Space Resources. Students approved to enroll in this program may double count up to six credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with "B" or better, not be substitutes for required coursework, and meet all other University, Department, and Program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

## Graduate Certificate

The Graduate Certificate is intended to give the student a panoramic view of space resources to understand the role that scientific knowledge, engineering systems, economic analyses, business cases, and legal and policy aspects play in this field. This option requires students to take a minimum of 12 credits online with 3 credits from Space Resources Fundamentals (SPRS501) and 9 credits chosen from other courses. Table 1 lists the courses that will comprise the curriculum for the Graduate Certificate.

**Table 1 – Required courses for 12-credit hour Graduate Certificate in Space Resources**

| | | |
|---|---|---|
| SPRS501 | SPACE RESOURCES FUNDAMENTALS | 3.0 |
| ELECTIVES | SPRS 502 or Elective courses chosen from Table 3 | 9.0 |
| **Total Semester Hrs** | | **12.0** |

Elective courses can be taken from a variety of important topics on space resources, such as: planetary geology, space operations, remote sensing, resource economics, materials extraction, advanced manufacturing, space law and policy, and other topics which continue to be introduced as relevant subjects are identified and new courses developed (see Table 3). Students are also allowed to take courses from other departments and programs with the approval from the Space Resources Program Director in consultation with faculty members of the program.

## Master of Science (Non-Thesis)

The Master of Science program is intended to give the degree holder the knowledge and skills to make immediate contributions to any government agency or company pursuing technical activities related to space resources. The Master of Science degree program is exclusively non-thesis (MS-NT) and online. The MS-NT degree program coursework requires 31 credits as laid out in Table 2, with 13 credits from five courses (SPRS501, SPRS502, SPRS503, SPRS591 and SPRS592) and 18 credits from elective courses. For students coming into the program with previous Master or PhD degrees, up to 9 credits of relevant courses can be transferred after approval from the Space Resources program director in consultation with faculty members of the program.

**Table 2 – Required courses for the 31-credit hour online Master of Science Non-Thesis degree in Space Resources**

| | | |
|---|---|---|
| SPRS501 | SPACE RESOURCES FUNDAMENTALS | 3.0 |
| SPRS502 | SPACE SYSTEMS ENGINEERING | 3.0 |
| SPRS503 | SPACE RESOURCES SEMINAR | 1.0 |
| SPRS591 | SPACE RESOURCES PROJECT I | 3.0 |
| SPRS592 | SPACE RESOURCES PROJECT II | 3.0 |
| ELECTIVES | Elective courses chosen from Table 3 | 18.0 |
| **Total Semester Hrs** | | **31.0** |

The 6 credits of project courses (SPRS 591 and 592) allow students to develop a design, system, or economic analysis focused on the exploration, extraction, utilization, and responsible stewardship of space resources. The 18 credits of elective courses can be selected from any of the various courses listed in Table 3. These courses provide students with a broad interdisciplinary coverage of critical areas in space resources, such as: Remote Sensing and Resource Assessment; Planetary Geology; Extraction, Processing, and Resource Utilization; Power and Energy; Robotics, Autonomy, and Communications; and Economics, Law, and Policy.

Additionally, new courses continue to be developed and introduced on various relevant subjects. Also, courses from other departments and programs at Mines are allowed as electives after approval from the Space Resources program director in consultation with faculty members of the program.

**Table 3 – Current elective courses for all degree options of the Space Resources program** (additional topics continue to be introduced as relevant subjects are identified and new courses developed). Other courses at Mines are also allowed after approval from the Space Resources program director in consultation with faculty members of the program.

| | | |
|---|---|---|
| AMFG501 | ADDITIVE MANUFACTURING | 3.0 |
| AMFG521 | DESIGN FOR ADDITIVE MANUFACTURING | 3.0 |
| AMFG522 | LEAN MANUFACTURING | 3.0 |
| CEEN501 | LIFE CYCLE ASSESSMENT | 3.0 |
| GEOL557 | EARTH RESOURCE DATA SCIENCE 1: FUNDAMENTALS | 3.0 |
| GEOL558 | EARTH RESOURCE DATA SCIENCE 2: APPLICATIONS AND MACHINE-LEARNING | 3.0 |
| MEGN551 | ADVANCED FLUID MECHANICS | 3.0 |
| MEGN566 | COMBUSTION | 3.0 |
| MEGN571 | ADVANCED HEAT TRANSFER | 3.0 |
| SPRS504 | ECONOMICS OF SPACE RESOURCES | 3.0 |
| SPRS505 | SPACE OPERATIONS | 3.0 |
| SPRS506 | INTERNATIONAL SPACE LAW & POLICY | 3.0 |
| SPRS507 | ADVANCED PLANETARY GEOLOGY | 3.0 |
| SPRS508 | REGOLITH PROPERTIES AND PROCESSING | 3.0 |
| NUGN598 | SPECIAL TOPICS (Introduction to Space Nuclear Technology) | 3.0 |
| SPRS598B | INNOV8X – ENTREPRENEURSHIP AND INNOVATION | 3.0 |
| SPRS599 | INDEPENDENT STUDY IN SPACE RESOURCES | 1-6 |

## PhD in Space Resources

The Doctor of Philosophy (PhD) is intended to provide the degree holders the necessary knowledge and research skills to pursue academic positions or contribute as a space-resources specialist in industry or government agencies. A student who completes a PhD in Space Resources will possess all the training of a Master's degree holder with further specialization in one or more areas within the space resources field. The completed doctoral dissertation will make original contributions to the field.

**1) General Requirements**

The Doctor of Philosophy (PhD) degree in Space Resources requires 72 total credits, consisting of at least 36 credits of courses beyond the BS and at least 24 research credits. The balance of 12 credits can be either course or research credits. Coursework beyond the MS degree program will not be restricted other than approved by the student's advisor and Dissertation Committee. The PhD degree allows for both on-campus and online options. The latter requires approval by the student advisor, Dissertation Committee, and Program Director who will review and approve if the research project can be conducted remotely. If a student requests to transfer from on-campus to online status (or vice versa) after passing the PhD Qualifying Exam, the Dissertation Committee will also have to approve the change in addition to the advisor.

For students coming into the PhD program with a Master Non-Thesis degree in an engineering, science, economics, or other relevant field, up to 24 credits of courses can be transferred, after approval from the Space Resources Program Director in consultation with the program faculty. These students will still be required to take 13 credits from five courses (SPRS501, SPRS502, SPRS503, SPRS591 and SPRS592) and other elective courses needed to complete the minimum 36 credit course requirement. For students with a previous Master with Thesis or PhD degree, up to 36 credits of relevant courses can be approved for transfer; however, the student will still be required to take the 13 credits from the previously mentioned five courses and other elective courses needed to complete the minimum 36 credit course requirement. For all students starting the PhD program already with a Mines Space Resources Certificate or MS-NT degree (or transferring to the PhD from any of these two programs), all credits taken at the Mines Space Resources program can be transferred to the PhD degree.

Students in the Space Resources PhD degree program must successfully complete a Qualifying Exam, defend a written Dissertation Research Proposal, submit at least one publication to a peer-reviewed journal, deliver conference and program seminar presentations, and write and defend a Doctoral Dissertation, in addition to their course and research work. PhD research is aimed at advancing fundamental knowledge in the Space Resources field. From the beginning of their studies at Mines, students must have an advisor to direct and monitor their academic plan, research, and independent studies. A PhD Dissertation Committee must also be assembled after passing the Qualifying Exam, as outlined below.

**2) PhD Qualifying Exam**

Students enrolled in the Space Resources PhD program are required to pass a Qualifying Exam. The PhD Qualifying Exam will be administered at specific dates during the year as determined by the Space Resources PhD Qualifying Exam Committee. The Committee will appoint an Exam Chair, who oversees the process and ensures that the Exam is administered fairly. The Qualifying Exam assesses attributes expected of a successful PhD student, including:

- Basic knowledge of the field of space resources represented by the core courses,
- Ability to review, synthesize, and apply fundamental concepts,
- Creative and technical potential to solve open-ended, challenging problems, and
- Verbal and written communication skills.

Students must take the exam at the first opportunity after completing the following requirements:

- Taken a total of 18 credits of course work (not including research thesis credits) with a minimum 3.3 GPA from all courses taken at Mines
- Taken SPRS501, SPRS502, SPRS503, SPRS591, and SPRS592. The latter can be taken concurrently with the exam during the same semester.

Students may petition the Committee for course waivers or deviation from these requirements. If the student fails the exam on the first attempt, he/she must retake the exam at the first opportunity. A maximum of two attempts is permitted.

To sign up for the Qualifying Exam, students must provide to the Exam Chair at a given deadline an updated *Space Resources Course Plan* and a *Statement of Intent* to take the exam at a particular opportunity. In the *Space Resources Course Plan,* the student will list all required five courses and technical electives taken, number of credits, and any waivers for courses requested. In the *Statement of Intent*, the student must explain how the Qualifying Exam Criteria will be met and the rationale for course waivers or deviations from the criteria, if requested. Waiving the five required courses is not encouraged. SPRS501 and SPRS502 can only be waived if a student has completed a substantially similar course. SPRS591 and SPRS592 can only be waived if a student has completed a MS degree with Thesis relevant to space resources or has substantial work experience in the space resources field.

For those students transferring courses (not replacing the required five courses) from previous Master's or PhD degrees, these courses should be listed as Technical Electives in the *Space Resources Course Plan*. The Exam Committee will review the *Course Plan* and *Statement of Intent* by the established deadline and determine if the student is ready to take the Exam.

The Qualifying Exam will consist of a written Research Review paper and an Oral Exam.

*a) Research Review Paper*. After the Committee has approved the request from the student to take the Qualifying Exam, the student will suggest in writing to the Committee Chair a topic that he/she would like to review for the Research section of the Qualifying Exam. Preferably, this topic should be related to the research the student is intending to pursue for his/her dissertation, but should not describe the student's current or proposed research project in any detail. The Qualifying Exam Committee will make the final decision on the topic assigned to each student. Students will be given at least four weeks to write a critical review of the topic. The review paper is to discuss the relevance of the topic to space resources, its current state in the field, and possible extensions of research in that area to fill current gaps.

*b) Oral Exam.* Once the Research Review paper has been submitted, an Oral Exam will be conducted by the PhD Exam Committee composed of a minimum of two faculty members and the student's advisor. The

Committee will specify the exam format in advance. The Oral Exam is structured as follows:

- It lasts between *90 and 120 minutes*,
- It is conducted in a synchronous video-conference,
- It starts with a 15-20 minute presentation on the Research Paper delivered by the student,
- It continues with 15-20 minutes of questions from faculty regarding the Research Paper, and
- The rest of the time consists of open-ended questions from faculty on any topic in space resources.

Qualifying Exam results of Pass, Conditional Pass, or Fail will be provided to the student in a timely manner by the Exam Chair. A Conditional Pass requires a student to pursue a remedial plan, which must be approved by the Qualifying Exam Committee.

**3) PhD Dissertation Committee:**

After passing the Qualifying Exam, the PhD student will meet with his/her advisor and select a Dissertation Committee. If the research topic of the student has changed significantly from the one initially intended, the student may select a new advisor (with the help of the original advisor), who will then help the student to select a Dissertation Committee. The Committee must have at least four members, including the advisor; at least two members must be permanent faculty in the Space Resources Program and at least one member must be from outside the program and be a faculty member at Mines. This outside member must chair the Committee. The student's advisor and Dissertation Committee must be approved by the Program Director. An Advisor/Thesis Committee form must then be submitted to the Office of Graduate Studies for its approval. Additional Committee members from outside Mines are allowed with the student's advisor approval.

**4) Research Proposal** The student should meet with the advisor and Dissertation Committee not long after its selection to discuss the research topic and obtain their feedback before starting the preparation of the Research Proposal, which consists of a document and a presentation. Other meetings prior to the presentation of the Proposal may be scheduled if the student, advisor, or Committee judges that it is needed. The student will then prepare a written Proposal of up to 10 pages (or more with Committee approval). The format is a single-spaced document with one-inch margins and 12-pt font. The document can include images and graphs; references and footnotes should be included in additional pages. The student will formally submit the Proposal to the Committee at least two weeks in advance of the date agreed upon by all for its presentation. The written Research Proposal is expected to achieve the following:

- Demonstrate a thorough familiarity with the background and motivation of the research problem being undertaken as embodied by a review of the relevant literature,
- Enumerate specific aims and/or hypotheses,
- Identify preliminary techniques, analyses, studies, materials, and in the case of experimental work, specific test objectives for the proposed research project,
- Explain clearly the merit ("value added") of the proposed work to the existing body of knowledge,
- Provide a general idea of the timeline for the research program, and
- Specify potential publications and presentations that may arise from the work.

The student and the advisor must convene a 2-hour meeting of the full Dissertation Committee in which the student will provide an oral summary of the written Proposal in a 30-45-minute presentation followed by questions from the Committee. This Proposal gives the Committee an early chance to discuss the research topic, help the student more clearly define the work to be accomplished, and identify the salient aspects of the proposed research. The Research Proposal presentation may be held the semester after successfully passing the Qualifying Exam, but preferably no later than one year after the Exam. The Research Proposal must be completed before admission to PhD candidacy. After passing the Research Proposal, it is highly recommended that the student and advisor keep the Committee informed of the student's work progress.

**5) Degree Audit and Admission to Candidacy**

PhD students must complete the Degree Audit form and the Admission to Candidacy form by the posted deadlines. For on-campus students, the Admission to Candidacy form must be submitted by the first day of classes of the semester in which they want to be considered eligible for reduced registration. Additionally, full-time PhD students should complete the following requirements within the first three years after enrolling into the PhD program:

- Have a Thesis Committee appointment form on file in the Graduate Office,
- Complete all prerequisite and curriculum course requirements,
- Demonstrate adequate preparation for, and satisfactory ability to conduct doctoral research,
- Be admitted into candidacy for the degree.

**6) Reduced Registration**

Students become reduced registration eligible once they have

1) earned 72 credit hours (combined coursework and research),
2) paid for 54 credit hours (including transfer of credit if applicable), and
3) achieved candidacy.

**7) Required Number of Publications and Presentations**

The required and recommended journal publications for PhD students prior to graduation are listed below. Students wanting to defend before meeting these requirements must submit a one-page petition with a reasonable explanation to the student advisor and the Committee.

*a) Journal publications* **-** Required: One first-author paper accepted or published in a peer-reviewed journal (recognized as high quality in the research field) before the Dissertation Defense. Recommended: Two or more first-author papers accepted or published in peer-reviewed journals. Three or more first-author journal publications are recommended for students interested in academic positions.

*b) Presentations* **-** Required: One research presentation (poster or podium) at an external technical conference before the Dissertation Defense. Three presentations in seminars within the Space Resources program or at Mines (such as the campus-wide graduate student research conference, online presentations during student research meetings or program seminars, research sponsor meetings, or additional conference presentations) during PhD program. Recommended: Two or more conference presentations (poster or podium) before the Dissertation Defense in which the student is the first author on these presentations. Numerous conference presentations are strongly encouraged to

establish a reputation amongst researchers in the field for students interested in academic positions.

**8) Dissertation Defense**

At the conclusion of the student's PhD program, the student will be required to write a Dissertation and make a formal presentation and Defense of his/her research. This Defense should be scheduled for at least 2 hours to give the student 45 minutes of presentation followed by questions from the general public attending the defense, and finally questions and discussion exclusively with the advisor and Dissertation Committee. A student must pass this Defense to earn a PhD degree, as determined by voting members of the Dissertation Committee. The Dissertation should be submitted to the Dissertation Committee at least two weeks prior to the Defense. The Committee will perform a post-presentation review of the Dissertation, technical contributions, and publications with the student. The Committee may request revisions to the Dissertation and additional work that requires subsequent review by the advisor and the Committee. These revisions should be incorporated to the Dissertation and the document formally submitted to the school after following all the Dissertation requirements and guidelines for its writing and publication.

**9) Unsatisfactory Progress**

To ensure that a student receives proper feedback if progress toward the Preliminary Defense or the Dissertation Defense is not satisfactory, the Advisor must provide the student and the Committee a brief, written progress evaluation. If the student's progress is unsatisfactory such that the Advisor gives them a PRU grade for research credits, the student will go on academic probation as outlined in the Graduate Catalog. Students must maintain good academic standing as defined by the Office of Graduate Studies. If the student falls out of good standing, Office of Graduate Studies policies to restore good standing must be followed in order to continue in the PhD program.

**10) Time Limit**

As stipulated by the Mines Graduate School, a candidate for a doctoral degree must complete all requirements for the degree within nine years of the date of admission into the degree program.

**SPRS501. SPACE RESOURCES FUNDAMENTALS. 3.0 Semester Hrs.**
(I,II) This course provides an overview of the space resources field, including the current knowledge of available resources in the Solar System, extraction and utilization systems under development, economic and technical feasibility studies, legal and policy issues, and space exploration architectures that may be enabled by utilizing extraterrestrial resources in the near future. The course will build broad knowledge and develop confidence in problem solving in the space resources field. This is an 8-week online course. Prerequisite: Working knowledge of physical sciences, engineering fields, or economics at an advanced undergraduate level, with basic numerical analysis skills using a programming language or spreadsheet calculations.
**Course Learning Outcomes**

- 1. Students will demonstrate knowledge of space resource exploration, resource availability, and technologies associated with their recovery, extraction, processing, and utilization
- 2. Students will exhibit understanding of current technological, economic, and policy challenges in space resources
- 3. Students will develop the ability to evaluate quantitatively and design a space-resource technology plan

**SPRS502. SPACE SYSTEMS ENGINEERING. 3.0 Semester Hrs.**
(I,II) This course conveys the fundamentals of the systems engineering process as applied to large, complex space systems. It is intended for graduate students with various backgrounds. The students will become familiar with full scope of the systems engineering process from requirements definition, system design, system analysis through system verification. The process will be illustrated with real-world examples from current space systems with an emphasis on systems relevant to the development of space resources. This is an 8-week online course. Prerequisite: SPRS501.
**Course Learning Outcomes**

- 1. Understand the logic steps of the systems engineering process for space systems
- 2. Understand the detailed objectives of each step in the process and become familiar with some of the standard industry tools.
- 3. Understand the wide range and applicability of analysis disciplines in assessing space systems.
- 4. Gain familiarity and develop intuition with the complex interactions among system elements and how proper operation can be verified.

**SPRS503. SPACE RESOURCES SEMINAR. 1.0 Semester Hr.**
(I, II) The Space Resources Seminar will engage students in the program with current research and developments related to space resources. Students will assess the importance and relevance to the space resources field in the near-, medium-, or long-term of topics covered in lectures presented by technical experts from a variety of disciplines. They will report and analyze events, news, and research publications and develop scientific, technical, and economic arguments for their impact and relevance to the space resources field, while also responding thoughtfully and critically to other students' contributions. Students will synthesize the information presented during the course in a final report with an analysis of the most important developments in the science, technology, economics and policy of space resources during the course period. This is an 16-week online seminar course.
**Course Learning Outcomes**

- Gain in-depth exposure to current research and development pertaining to space resource.
- 2. Develop student's skills at professional communication through giving their own presentation and evaluating those of others.
- 3. Understand professional expectations for technical experts in the space resources field through assessing industry, government, and academic opportunities.

**SPRS504. ECONOMICS OF SPACE RESOURCES. 3.0 Semester Hrs.**
(I,II) This course provides an overview of economics and business topics that are commonly found in the space industries. Students will build a basic knowledge of economics, finance, and business issues that are relevant to space resource markets and industries. The big picture is to help provide perspective on what investors or the financial officers at companies are investing in and planning for in or around the space industry. Prerequisite: SPRS501.
**Course Learning Outcomes**

- Interpret and assess basic economic intuition and lingo so that one can contribute to projects on the business side
- Evaluate and critique standard investment analysis techniques
- Describe common market structures for natural resource commodities and theorize its impact on firm behavior

- Name the location of basic data on natural resource price, production, and consumption and demonstrate its evolution over time
- Design a presentation for the business community that provides a clear value proposition
- Execute an "elevator pitch" (concise and persuasive speech to spark interest) about a Space Resource topic

**SPRS505. SPACE OPERATIONS. 3.0 Semester Hrs.**
(I,II) This course explores the people, events, missions, operations, and basic system principles that have shaped the space industry. It is intended for graduate students with various backgrounds. Students will become familiar with space operations principles through work in orbital mechanics, space environments analysis, as well as mission and spacecraft design. Students will evaluate a broad range of existing missions and architectures from different perspectives through various case studies and discussions and will apply these concepts to the preliminary design of a space mission. Eight-week online course with asynchronous web content and no on-campus lectures, but with two synchronous, one-hour videoconferencing sessions per week. Prerequisite: SPRS501.
**Course Learning Outcomes**

- 1. Analyze the influence of policy, politics, physics on the history and evolution of the space industry
- 2. Integrate and outline characteristics, operations, and suitability of launch systems and spacecraft missions
- 3. Calculate and estimate preliminary spacecraft subsystem parameters and architecture
- 4. Articulate a space mission motivation and objectives that support space resources
- 5. Apply design principles to iterate and optimize across multiple subsystem interactions and top-level requirements
- 6. Develop an integrated preliminary spacecraft mission and bus design solution that synthesizes learning

**SPRS506. INTERNATIONAL SPACE LAW & POLICY. 3.0 Semester Hrs.**
(II) This course will familiarize students with the fundamentals of international space law, and train students to think critically about issues of space law and policy as human utilization of space continues to grow and change. Students will be exposed to new ways of thinking-spotting issues and applying what is learned in order to analyze issues of space law. It is intended for graduate students with various backgrounds. This is an 8-week online course. Prerequisite: SPRS501.
**Course Learning Outcomes**

- 1. Define, classify, and apply international law to the law of outer space, its associated fields, and the applicable rules, regulations, and policies
- 2. Explain the role played by the United Nations in creating and maintaining the Outer Space Treaty regime
- 3. Critically analyze the multilateral agreements between States that make up the main body of international space law
- 4. Articulate the principles and evaluate the policy reasoning as well as ethical considerations underlying the past, present, and future uses of space for civil, military, and commercial development, particularly space resource utilization
- 5. Identify, interpret, and examine problems and gaps in international space law with a view to future problem solving
- 6. Apply space law and learn to develop effective policy recommendations when presented with real world or hypothetical scenarios
- 7. Explain the relationship between international space law and domestic space law

**SPRS507. ADVANCED PLANETARY GEOLOGY. 3.0 Semester Hrs.**
(I,II) This course provides a detailed look at planetary bodies, from atmosphere to surface to interior. The focus is on the geological processes that have formed then transformed these bodies over time, with special attention paid to the formation of space resources. These processes include accretion and differentiation, impact cratering, tectonics, geodynamics, volcanism, erosion and deposition, and chemical weathering, among others. Schedule Type: Eight-week online course with asynchronous web content and no on-campus lectures, but with two synchronous, one-hour videoconferencing sessions per week. Prerequisite: SPRS501.
**Course Learning Outcomes**

- Use order of magnitude estimation and/or provided formulas to solve quantitative problems for geologic processes including accretion, differentiation, impact cratering, volcanism, and mass transport.
- Create and interpret visual plots used to convey the composition and physical state of planetary materials, including phase diagrams, Ellingham diagrams, and ternary plots.
- Judge the resource potential of planetary bodies and specific locations on those bodies, in terms of the type, concentration, and distribution.
- Conjecture about counterfactual scenarios related to specific planetary bodies and events in solar system history.
- Construct and interpret map products from planetary datasets using GIS tools.
- Evaluate planned architectures from space mining companies and public statements about space resources on the basis of their geological plausibility, and potential challenges that could be faced based on actual conditions on the ground.

**SPRS509. SPACE ROBOTICS. 3.0 Semester Hrs.**
This online course introduces students to the design, analysis, and operation of robotic spaceflight missions. By integrating space exploration with robotics, students will explore planetary science questions, develop mission plans, and evaluate the technologies required to achieve mission objectives. Topics include sensor systems, automation trade-offs, and rover mobility. The course prepares students for careers in aerospace and robotics by providing essential technical, analytical, and organizational skills to solve complex challenges in these fields. Prerequisite: SPRS501.
**Course Learning Outcomes**

- Identify state of the art planetary science questions and technology goals from the 2023 origins, worlds, and life (OWL) planetary science decadal survey.
- Illustrate the evolution of spaceflight technologies for planetary surface robots, specifically around rover mobility and sensing.
- Design an extraplanetary surface robotic mission with a science or technology goal derived from OWL.
- Assess the data signals from sensors necessary to produce the end data product, which is informed by the science or technology goal.
- Plan the mission operations and robot actuators necessary to achieve mission objectives.

- Differentiate operations between robot automation and human teleoperation along the metrics of risk, SWaP, complexity, and timeline.
- Develop a perception framework and path planning strategy informed by mission requirements and a concept of operations.
- Execute basic mobility algorithms constrained by robot capabilities and limitations in Moon environment.

**SPRS591. SPACE RESOURCES PROJECT I. 3.0 Semester Hrs.**
This course will provide graduate students in the program with directed team-based project learning by exploring the design, planning, and analysis of missions, processes, systems, science, business, and economics for space resources assessment, extraction, and utilization. The course will meet formally online once a week for one hour and include a discussion on relevant design aspects of space mission, processes, and/or systems. In this regard, it will build on content learned in the Space Resources Fundamentals, Space Systems Engineering, and other courses in the Space Resources Program. Students will collaborate in multi-disciplinary teams and will be advised by a course instructor with significant industrial design experience and supported by faculty affiliated with the Space Resources program from relevant disciplines on campus. For teams with students in space resource economics, detailed economic analyses will be incorporated into those projects. Student teams will prepare a preliminary design, planning and analysis report early in the semester, one interim progress report, and a final report and project presentation. This is a 16-week online course. Prerequisite: SPRS501 and SPRS502.
**Course Learning Outcomes**

- 1. Learn principles and best practices in space systems design, mission, planning, and resource analysis
- 2. Develop student's confidence through practice at design, planning, and analysis for missions,systems, economics, business, and science related to space resources.
- 3. Gain practice in written and oral presentations of design and analysis of space systems.

**SPRS592. SPACE RESOURCES PROJECT II. 3.0 Semester Hrs.**
This course will provide graduate students in the Masters and PhD programs in Space Resources with an independent design and analysis project. This project will be guided by the course instructor and a technical advisor, and will enable the student to delve deeply into a particular system related to the prospecting, extraction, processing, and utilization of potential space resources, as well as business and economics cases in this field. As much as possible, projects will be coordinated with industrial or government agency partners who are collaborating with the program. The course will involve weekly online meetings where ideas are exchanged and progress discussed within the context of design and analysis principles learned in the prerequisite courses. Students will be partnered with a faculty member affiliated with the Space Resources Program. The student will prepare a final report and presentation to present to industry collaborators, space resources faculty, and other students in the course. The final report and/or presentation as appropriate will be converted to a journal publication, conference publication and/or research proposal and resources from the program will support student costs for publishing and/or presenting the work. This is a 16-week online course. Prerequisite: SPRS501, SPRS502, SPRS591.
**Course Learning Outcomes**

- 1. Develop a level of expertise and understanding of a technology opportunity in space resources.
- 2. Raise student's confidence through practice at design, planning, and analysis for missions and systems related to space resources.
- 3. Gain practice in written and oral technical presentations of design and analysis of space systems.

**SPRS598. SPECIAL TOPICS IN SPACE RESOURCES. 6.0 Semester Hrs.**
(I, II, S) Pilot course or special topics course. Topics chosen from special interests of instructor(s) and student(s). Usually the course is offered only once, but no more than twice for the same course content. Prerequisite: SPRS501. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.

**SPRS599. INDEPENDENT STUDY IN SPACE RESOURCES. 0.5-6 Semester Hr.**
(I, II, S) Students can do Individual research or special projects supervised by a faculty member. The student and instructor will agree on the subject matter, content, and credit hours. Prerequisite: SPRS501

**SPRS707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.**
(I, II, S) Research credit hours required for completion of Doctoral dissertation. Research must be carried out under the direct supervision of the student's faculty advisor. Variable class and semester hours. Repeatable for credit. Prerequisite: Instructor approval.

## CORE FACULTY

### Director and Professor of Practice

Angel Abbud-Madrid

### Professor of Practice

Christopher Dreyer

George Sowers

### Assistant Professor

Frankie Zhu

### Additional Information

Adjunct teaching instructors and faculty from several departments at Mines are also affiliated with the program and teach courses, supervise independent and course projects, act as thesis advisors, and conduct research. A list of current adjunct and affiliated faculty members can be found at: https://space.mines.edu/faculty/

# Underground Construction and Tunnel Engineering

## Program Description

Underground Construction and Tunnel Engineering (UCTE) is an interdisciplinary field primarily involving civil engineering, construction engineering, geological engineering, and mining engineering, and secondarily involving mechanical engineering, geophysics, geology, and others. UCTE deals with the design, construction, rehabilitation and management of underground space including caverns, shafts and tunnels for commercial, transportation, water and wastewater use. UCTE is a challenging field involving complex soil and rock behavior, groundwater conditions, excavation methods, construction materials, structural design,

heterogeneity, and very low tolerance for deformation due to existing infrastructure in urban environments. Students pursuing a graduate degree in UCTE will gain a strong interdisciplinary foundation in these topics.

## Program Contact

Program Director: Michael Mooney

ucte.mines.edu

Program Coordinator: Rachel McDonald

## Program Requirements

## Master's and PhD in Underground Construction and Tunneling Engineering

**MS Non-Thesis Option:**

| |
|---|
| Coursework - 27.0 credits |
| Independent Study* - 3.0 credits |
| UCTE Seminar - 0.0 credits |
| Total Hours - 30.0 |

*Where possible, MS non-thesis students should complete a practically focused independent study in partnership with an industry partner; this may include student participation in an industry internship on a UCTE project.

**MS Thesis Option:**

| |
|---|
| Coursework - 24.0 credits |
| Research (minimum) - 6.0 credits |
| UCTE Seminar - 0.0 credits |
| Total Hours - 30.0 |

MS thesis students must write and successfully defend a thesis report of their research. Ideally, MS thesis research should be industry-focused and should provide value to industry UCTE practice.

**PhD Option**

| |
|---|
| Coursework (beyond BS degree) - 42.0 credits |
| Independent Study* - 3.0 credits |
| Research (minimum) - 24.0 credits |
| UCTE Seminar - 0.0 credits |
| Total Hours - 72.0 |

PhD students must also successfully complete qualifying examinations, write and defend a dissertation proposal, and write and defend a doctoral dissertation. PhD research is aimed at fundamentally advancing the state of the art in UCTE. PhD students are expected to submit the dissertation work for publication in scholarly journals and disseminate findings throughout industry periodicals.

*PhD students are expected to complete an internship of approximately three months in duration (with a design firm, contractor, owner, equipment manufacturer, etc., and preferably on a UCTE job site). If an internship is not available or if the student has sufficient industry experience (determined by advisor and committee), the student may complete an industry-focused research project via independent study with a UCTE faculty member and industry partner culminating with a written report and presentation.

## Mines' Combined Undergraduate/Graduate Degree Program

Students enrolled in Mines' combined undergraduate/graduate program may double count up to 6 credits of graduate coursework to fulfill requirements of both their undergraduate and graduate degree programs. These courses must have been passed with B- or better, not be substitutes for required coursework, and meet all other university, department, and program requirements for graduate credit.

Students are advised to consult with their undergraduate and graduate advisors for appropriate courses to double count upon admission to the combined program.

## Required Coursework

The following 15 credits are required for the MS (thesis and non-thesis) and PhD degrees.

| | | |
|---|---|---|
| GEGN561 | UNDERGROUND CONSTRUCTION ENGINEERING LABORATORY | 1.0 |
| GEGN572 | ENGINEERING GEOLOGY AND GEOTECHNICS | 4.0 |
| MNGN504 | UNDERGROUND CONSTRUCTION ENGINEERING IN HARD ROCK | 3.0 |
| CEEN523 | UNDERGROUND CONSTRUCTION ENGINEERING IN SOFT GROUND | 4.0 |
| CEEN532 | UNDERGROUND INFRASTRUCTURE CONSTRUCTION MANAGEMENT | 3.0 |
| or MNGN509 | CONSTRUCTION ENGINEERING AND MANAGEMENT | |

All MS and PhD students are required to attend the UCTE seminar series (0 hour); no registration is required.

MS non-thesis and PhD students must complete a practically-focused project (separate from the thesis in the case of the PhD degree), registering as an independent study in the home department of the faculty advisor (CEEN599, GEGN599, or MNGN599). This requirement may be waived for students with sufficient UC&T industry experience.

## Elective Coursework

The following courses may be taken as electives to complete the MS and PhD course requirements. Students may petition for other courses not listed below to count toward the elective requirement. In addition, MS or PhD students may petition one of the following courses to substitute for a required course if one of the required courses is not offered during the student's course of study or if a student has sufficient background in one of the required course topics. All petitions must be made to the student's advisor and thesis committee.

| | | |
|---|---|---|
| CEEN506 | FINITE ELEMENT METHODS FOR ENGINEERS | 3.0 |
| CEEN510 | ADVANCED SOIL MECHANICS | 3.0 |
| CEEN512 | SOIL BEHAVIOR | 3.0 |
| CEEN541 | DESIGN OF REINFORCED CONCRETE STRUCTURES II | 3.0 |
| CEEN599 | INDEPENDENT STUDY | 0.5-6 |
| GEGN563 | APPLIED NUMERICAL MODELLING FOR GEOMECHANICS | 3.0 |
| GEGN566 | GROUNDWATER ENGINEERING | 3.0 |
| GEGN573 | GEOLOGICAL ENGINEERING SITE INVESTIGATION | 3.0 |

| | | |
|---|---|---|
| GEGN581 | ANALYTICAL HYDROLOGY | 3.0 |
| GEGN672 | ADVANCED GEOTECHNICS | 3.0 |
| GEGN673 | ADVANCED GEOLOGICAL ENGINEERING DESIGN | 3.0 |
| GEGN599 | INDEPENDENT STUDY IN ENGINEERING GEOLOGY OR ENGINEERING HYDROGEOLOGY | 0.5-6 |
| MNGN506 | DESIGN AND SUPPORT OF UNDERGROUND EXCAVATIONS | 3.0 |
| MNGN507 | ADVANCED DRILLING AND BLASTING | 3.0 |
| MNGN524 | ADVANCED MINE VENTILATION | 3.0 |
| MNGN590 | MECHANICAL EXCAVATION IN MINING | 3.0 |
| MNGN599 | INDEPENDENT STUDY IN MINING ENGINEERING | 0.5-6 |

## Thesis Committee Requirements

Students must meet the general committee requirements listed in the graduate bulletin. In addition, the student's advisor or co-advisor must be a UCTE faculty member. In the case that a student is co-advised, the co-advisor will serve as an additional committee member above and beyond the minimum committee requirements.

The committee for PhD students enrolled in the UCTE degree program shall be composed of a minimum of four faculty members:

- The student's advisor
- Two core UCTE faculty members representing two of three core UCTE departments (Civil Engineering, Geological Engineering, Mining Engineering)
- An external committee member, who has no connection to the student or their research (this member should not come from any of the three core UCTE departments, other than in exceptional circumstances); this member will chair the committee and must be a permanent Mines faculty member

Additional committee members may be added as appropriate, including off-campus representatives from industry and academia.

Given the interdisciplinary nature of the UCTE degree program, no more than two of the four PhD committee members can be from the same department.

## Qualifying Exam Procedure

Students enrolled in the UCTE PhD program are expected to have passed a qualifying exam by the end of their first year of study. This qualifying exam will be administered by a sub-committee of UCTE faculty. If a UCTE faculty member is serving on this sub-committee for the qualifying exam of a student they are advising, they will act as a non-voting member for that exam.

The intention of the qualifying exam is to evaluate the student's capacity to undertake PhD-level research; this includes their ability to think critically, to apply core UCTE concepts to abstract problems, and to develop methods to test scientific hypotheses. The format of the exam will include a written component and an oral exam, approximately two hours in length. Prior to their oral exam, the student will be assigned two tasks:

- The student will be provided a research topic which has some relevance to their research, but is not directly related. The student will be required to submit an 8–10 page literature review on this topic to their committee 24 hours prior to their oral exam. During the oral exam, the student will be asked questions related to their literature review.
- The student will be provided with four questions which will represent a significant portion of their oral exam. These questions will be designed to assess the student's ability to consider analysis, design, and research questions critically. The core UCTE curriculum will serve as foundational knowledge for these questions. As the student's response will be oral (no written response to the questions will be submitted), the questions will require students to suggest problem solving approaches rather than to directly implement them. Based on the student's response to each question, follow-up questions will be asked.

If the student fails their first qualifying exam, they may be given an opportunity to attempt a second qualifying exam at the discretion of the committee who administered their first exam. If the student fails their second qualifying exam, they will not be admitted to PhD candidacy.

## Prerequisites

Students will enter the UCTE programs with a variety of backgrounds. Because the UCTE degrees are engineering degrees, the required prerequisite courses for the UCTE programs include basic engineering coursework, and specifically: 1) Strength of Materials or Mechanics of Materials, and 2) Fluid Mechanics. These prerequisite courses may be completed during the first semester of the graduate program if approved by the UCTE program faculty. It is permissible for students to take graduate-level courses without having completed the corresponding undergraduate courses to address areas where key competencies are lacking, such as in soil mechanics, rock mechanics, structural analysis or groundwater engineering. However, students may choose to complete undergraduate courses in these topics prior to or concurrently during enrollment in the required graduate program courses. Undergraduate-level coursework to address any prerequisite deficiencies does not count toward the requirements of the MS or PhD degrees. Students should consult with UCTE faculty for guidance in this matter.

## Program Requirements

## Graduate Certificate in Underground Construction and Tunnel Engineering

The interdisciplinary Graduate Certificate in Underground Construction and Tunnel Engineering (UCTE) is comprised of the three signature courses listed below. The two anchor courses teach UCTE in hard rock and soft ground while the remaining course teaches underground infrastructure construction management principles.

Applicants for the certificate are required to be admitted into the combined BS + MS program or have an undergraduate degree in science or engineering, with geotechnical and mechanics of materials coursework, to be admitted into the certificate program. Students working toward the UCTE graduate certificate are required to successfully complete 10 credits, as detailed below. The courses taken for the graduate certificate can be used towards a master's or PhD degree at Mines.

| | | |
|---|---|---|
| CEEN523 | UNDERGROUND CONSTRUCTION ENGINEERING IN SOFT GROUND | 4.0 |
| CEEN532 | UNDERGROUND INFRASTRUCTURE CONSTRUCTION MANAGEMENT | 3.0 |

| | | |
|---|---|---|
| or MNGN509 | CONSTRUCTION ENGINEERING AND MANAGEMENT | |
| MNGN504 | UNDERGROUND CONSTRUCTION ENGINEERING IN HARD ROCK | 3.0 |
| **Total Semester Hrs** | | **10.0** |

## Program Director

Michael Mooney, UCTE Director, Grewcock Distinguished Chair

## Department of Civil & Environmental Engineering

Reza Hedayat, Associate Professor

Michael Mooney, Grewcock Distinguished Chair & Professor

Yangming Shi, Assistant Professor

Lori Tunstall, Assistant Professor

Alexandra Wayllace, Teaching Associate Professor

## Department of Geology & Geological Engineering

Gabriel Walton, Associate Professor

## Department of Mining Engineering

Rennie Kaunda, Assistant Professor

Priscilla Nelson, Professor

Jamal Rostami, Professor

# Combined Undergraduate/ Graduate Degree Programs

## OVERVIEW

Many degree programs offer Mines undergraduate students the opportunity to begin work on a professional master's degree, master's degree, or doctoral degree while completing the requirements for their bachelor's Degree. These combined bachelors–masters/doctoral programs have been created by Mines faculty in those situations where they have deemed it academically advantageous to treat undergraduate and graduate degree programs as a continuous and integrated process.

These are accelerated programs that can be valuable in fields of engineering and applied science where advanced education in technology and/or management provides the opportunity to be on a fast track for advancement to leadership positions. These programs can be valuable for students who want to get a head start on graduate education.

1. The combined programs at Mines offer several advantages to students who choose to enroll in them:
2. Students can earn a graduate degree in their undergraduate major or in a field that complements their undergraduate major.
3. Students who plan to go directly into industry leave Mines with additional specialized knowledge and skills which may allow them to enter their career path at a higher level and advance more rapidly. Alternatively, students planning on attending graduate school can get a head start on their graduate education.
4. Students can plan their undergraduate electives to satisfy prerequisites, thus ensuring adequate preparation for their graduate program.
5. Early assignment of graduate advisors permits students to plan optimum course selection and scheduling in order to complete their graduate program quickly.
6. Early acceptance into a combined degree program leading to a graduate degree assures students of automatic acceptance into full graduate status if they maintain good standing while in early-acceptance status.
7. In many cases, students will be able to complete both a bachelor's and a master's degrees in five years of total enrollment at Mines.

Students accepted into a combined program may substitute up to six credits of graduate coursework (500-level) to fulfill requirements of both their undergraduate degree and their graduate degree. These courses are referred to as double-counted courses and must be completed with a grade of B- or better. If a course (required or elective) is cross listed as 4xx/5xx, the 500-level version must be used for substitution purposes to be double counted. Additionally, combined undergraduate students who register for a 500-level graduate course will by default have courses applied to the graduate record. The credits will be recorded on the graduate transcript and the credits will impact the graduate level GPA. Students should work closely with their advisor to select the courses that will be moved to the undergraduate record for double counting by the add/drop date of the term in which the course is taken

**ENROLLING IN GRADUATE COURSES FOR A COMBINED PROGRAM**

Once admitted into a graduate degree program, undergraduate students may enroll in 500-level courses.

Financial aid may be impacted. Email finaid@mines.edu for more information on financial aid impacts.

In addition, undergraduate seniors who have been granted admission through the combined degree program into thesis-based degree programs (master's or doctoral) may, with graduate advisor approval, register for 700-level research credits appropriate to their degree programs. With this single exception, while a combined degree program student is still completing their undergraduate degree, all of the conditions described in the undergraduate catalog for undergraduate enrollment in graduate-level courses apply. 700-level research credits are always applied to a student's graduate degree program.

# Policies and Procedures

## Standards, Codes of Conduct

Students can access campus rules and regulations, including the student code of conduct, alcohol policy, public safety and parking policies, the distribution of literature and free speech policy, and a variety of others by visiting the school's policy website. We encourage all students to review the website and expect that students know and understand the campus policies, rules and regulations as well as their rights as a student. Questions and comments regarding the above-mentioned policies can be directed to the Dean of Students located in the Student Life Office in the Ben Parker Student Center.

For emphasis, the following policies are included or identified in this section:

- Student Honor Code
- Policy on Academic Integrity/Misconduct
- Policy Prohibiting Sexual Harassment, Sexual Violence, and Interpersonal Violence
- Unlawful Discrimination Policy
- Alcohol and Other Drugs Education and Prevention Policy
- Electronic Communications (Email) Policy
- Student Complaint Process
- Access to Student Records
- Posthumous Degree Awards
- Equal Opportunity, Equal Access, and Affirmative Action
    - Office of Institutional Equity & Title IX
    - SpeakUP@Mines

Please note: Any policy or procedure updates during the term will be reflected in the Mines Policy Library and those versions shall control.

## Student Honor Code

**1.0 PREAMBLE**

The students of Colorado School of Mines have adopted the following Student Honor Code in order to establish a high standard of student behavior at Mines. The code may only be amended through a student referendum supported by a majority vote of the Mines student body. Mines students shall be involved in the enforcement of the code through their participation in the Student Conduct Appeals Board.

**2.0 CODE**

Mines students believe it is our responsibility to promote and maintain high ethical standards in order to ensure our safety, welfare, and enjoyment of a successful learning environment. Each of us, under this code, shall assume responsibility for our behavior in the area of academic integrity. As a Mines student, I am expected to adhere to the highest standards of academic excellence and personal integrity regarding my schoolwork, exams, academic projects, and research endeavors. I will act honestly, responsibly, and above all, with honor and integrity in all aspects of my academic endeavors at Mines. I will not misrepresent the work of others as my own, nor will I give or receive unauthorized assistance in the performance of academic coursework. I will conduct myself in an ethical manner in my use of the library, computing center, and all other school facilities and resources. By practicing these principles, I will strive to uphold the principles of integrity and academic excellence at Mines. I will not participate in or tolerate any form of discrimination or mistreatment of another individual.

## Policy on Academic Integrity/Misconduct

**1.0 ACADEMIC INTEGRITY**

Colorado School of Mines (Mines) affirms the principle that all individuals associated with the Mines academic community have a responsibility for establishing, maintaining, and fostering an understanding and appreciation for academic integrity. In broad terms, this implies protecting the environment of mutual trust within which scholarly exchange occurs, supporting the ability of the faculty to fairly and effectively evaluate every student's academic achievements, and giving credence to the university's educational mission, its scholarly objectives, and the substance of the degrees it awards. The protection of academic integrity requires there to be clear and consistent standards, as well as confrontation and sanctions when individuals violate those standards. Colorado School of Mines desires an environment free of any and all forms of academic misconduct and expects students to act with integrity at all times.

**2.0 POLICY ON ACADEMIC MISCONDUCT**

Student academic misconduct arises when a student violates the principle of academic integrity and/or when a student aids and abets in the commission of academic misconduct. Academic misconduct may also occur when a student is negligent in their reasonable responsibilities as a student to be aware of or proactively confirm or clarify appropriate conduct with coursework, assignments or exams, and subsequently proceeds in a manner befitting of misconduct. Such behavior erodes mutual trust, distorts the fair evaluation of academic achievements, violates the ethical code of behavior upon which education and scholarship rest, and undermines the credibility of the university.

Because of the serious institutional and individual ramifications, student misconduct arising from violations of academic integrity is not tolerated at Mines. If a student is found to have engaged in such misconduct sanctions such as change of a grade, loss of institutional privileges, or academic suspension or dismissal may be imposed.

The Dean of Students Office administers this faculty-approved policy. Within the Dean of Students Office, two administrators will facilitate the separate aspects of the policy, including the initial resolution and appeal process, in order to remain impartial with respect to potential appeals while simultaneously providing procedural guidance to faculty and students.

**Forms of Misconduct**. As a guide, some of the more common forms of academic misconduct are noted below. This list is not intended to be all-inclusive; rather, the list is illustrative of practices the Mines faculty have deemed inappropriate.

1. **Dishonest Conduct** – general conduct unbecoming a scholar. Examples include issuing misleading statements; withholding pertinent information; submitting previously graded work as new and/or original without acknowledgment and permission; not fulfilling, in a timely fashion, previously agreed to projects or activities; and

verifying as true things that are known to the student not to be true or verifiable.

2. **Plagiarism** – presenting the work of another as one's own. This is usually accomplished through the failure to acknowledge the borrowing of ideas, data, or the words of others. Examples include submitting as one's own work the work of another student, a ghost writer, or a commercial writing service; quoting, either directly or paraphrased, a source without appropriate acknowledgment; and using figures, charts, graphs, or facts without appropriate acknowledgment. Inadvertent or unintentional misuse or appropriation of another's work is nevertheless plagiarism.
3. **Falsification/Fabrication** – inventing or altering information. Examples include inventing or manipulating data or research procedures to report, suggest, or imply that particular results were achieved from procedures when such procedures were not actually undertaken or when such results were not actually supported by the pertinent data; false citation of source materials; reporting false information about practical, laboratory, or clinical experiences; falsifying attendance or participation; submitting false excuses for absence, tardiness, or missed deadlines; and altering previously submitted examinations.
4. **Tampering** – interfering with, forging, altering, or attempting to alter university records, grades, assignments, or other documents without authorization. Examples include using a computer- or false-written document to change a recorded grade; altering, deleting, or manufacturing any academic record; and gaining unauthorized access to a university record by any means.
5. **Cheating** – using or attempting to use unauthorized materials or aid with the intent of demonstrating academic performance through fraudulent means. Examples include copying from another student's paper or receiving unauthorized assistance on a homework assignment, quiz, test, or examination; using books, notes, or other devices such as calculators, PDAs, and cell phones, unless explicitly authorized; acquiring without authorization a copy of the examination before the scheduled examination; and copying reports, laboratory work, or computer files from other students. Authorized materials are those generally regarded as being appropriate in an academic setting, unless specific exceptions have been articulated by the instructor.
6. **Impeding** – negatively impacting the ability of other students to successfully complete course or degree requirements. Examples include removing pages from books and removing materials that are placed on reserve in the library for general use; failing to provide team members necessary materials or assistance; and, knowingly disseminating false information about the nature of a test or examination.
7. **Sharing Work** – giving or attempting to give unauthorized materials or aid to another student. Examples include allowing another student to copy your work; giving unauthorized assistance on a homework assignment, quiz, test, or examination; providing, without authorization, copies of examinations before the scheduled examination; posting work on a website for others to see; and sharing reports, laboratory work or computer files with other students.

Additionally, individual courses may specify appropriate and/or inappropriate scholastic conduct as long as course-specific guidance is not in conflict with this senior university misconduct policy and is well known by way of advanced written distribution to all students enrolled (e.g., published course syllabus). Students are encouraged to seek prior authorization and permission to use online homework or tutoring sites including, but not limited to, CHEGG. The Academic Misconduct Policy prohibits unauthorized help or assistance. Unauthorized use of CHEGG or similar sites to the benefit of studying, homework, or examinations may result in academic misconduct investigations/sanctions. Viewing, uploading, and downloading material is not tolerated when the course material was illegally or improperly uploaded. Contact your faculty member to proactively seek permission or clarity.

Allegations of misconduct brought forward by faculty must fall within with the aforementioned seven examples of common misconduct and/or be specifically and explicitly addressed in the published course materials.

**3.0 PROCEDURES FOR ADDRESSING ACADEMIC MISCONDUCT**

Faculty members and thesis committees have discretion to address and resolve misconduct matters in a manner that is commensurate with the infraction and consistent with the values of the Institution. This includes imposition of appropriate academic sanctions for students involved in academic misconduct. However, in order to maintain consistency when handling such issues, if a member of the Mines' community has grounds for suspecting that a student or students have engaged in academic misconduct, they have an obligation to act on this suspicion by utilizing the following procedure:

**3.1 Notify the Dean of Students Office.** Upon suspicion of misconduct, it is the faculty member's responsibility to email the Dean of Students Office (deanofstudents@mines.edu). The Dean of Students Office will provide procedural guidance to the faculty member, including pre-written email templates which the faculty may use.

Student names may be disclosed at this time, but are not necessary. Prepared sample templates and procedural guidance will consider and include appropriate accessibility language to ensure an accessible process for students and faculty, alike.

**3.2 Notify and Meet with Student(s)**. Following correspondence with the Dean of Students Office, the faculty member or thesis committee representative must meet with and inform the student(s) of the suspicions/allegations and potential charge of academic misconduct within 10 business days of suspecting misconduct.

This meeting allows the student the opportunity to give their perspective or explanation prior to any decision being made as to whether or not misconduct occurred. The student should be aware of the subject of the meeting and the alleged misconduct at the time of scheduling. The meeting also allows the faculty member to have a conversation with the student(s) in an effort to educate them on appropriate conduct.

Following this meeting (at end of meeting or afterward and within the prescribed timeline), the faculty member should inform the student of their decision as to whether or not misconduct occurred. In the instance where the faculty member(s) believe misconduct occurred, the student should be explicitly informed of the nature of the misconduct (e.g., cheating, plagiarism, etc.).

The meeting can be done via telephone if needed, but a face-to-face meeting between the faculty member and student is preferred. It is recommended, but not required, that the faculty invite a neutral, silent colleague to the meeting as an impartial witness. If the student or faculty member is unable to meet because of pre-existing commitments or unforeseen priorities, the ten-day timeline may be temporarily suspended with mutual written agreement of faculty

and student(s), and written approval by the Dean of Students Office prior to expiration of the deadline.

**3.3. Actions Taken; Circumstances.** The circumstances of the academic misconduct dictate the process to be followed:

3.3.1 Regular Coursework. In the case of an allegation of academic misconduct associated with **regular coursework** (including exams), if after talking with the student, the faculty member finds the student is responsible for academic misconduct the faculty member should:

- Report the violation via this form (or via deanofstudents@mines.edu) within five business days of meeting with the student (as outlined above – see 3.1). The reporting form will collect necessary information on the student(s), violation(s), and course details. Report of a violation should detail the nature of the misconduct (e.g., cheating, plagiarism, etc.). A submitted form will automatically inform the Dean of Students Office.
- The Dean of Students Office will communicate the resolution in writing to the student, the faculty member(s), appropriate members of Academic Affairs, the Office of Graduate Studies (if applicable), the student's advisor, and any additional appropriate parties including Athletics, course coordinators, or the Registrar's Office. The Dean of Students will keep official records on all students with academic misconduct violations. Disciplinary action/ sanctioning for misconduct with regular coursework:
  - First Offense: Zero credit (or no points) on the assignment/exam/effort. Educational sanctioning as prescribed and facilitated by the Dean of Students Office. Notation of first offense in disciplinary record.
    - Failure to comply with educational sanctioning expectations and timeline will result in immediate acceleration of offense to sanctioning prescribed with second offense (F in course and inability to withdraw). Additionally, the student's disciplinary standing will also be upgraded to second offense.
    - With first offense, faculty may choose to provide a restorative credit assignment or make-up quiz or exam wherein students can work to recover credit penalized as part of misconduct sanctioning.
  - Second Offense: F in the course and inability to withdraw. Notation of second offense in disciplinary record.
  - Third or Greater Offense: F in the course. Suspension from school for one-year minimum (calendar year). "Suspension as a result of Academic Misconduct" permanently noted on university transcript. Return to Mines not guaranteed, and only possible by way of Mines Readmissions Committee.

3.3.2 Activities Not Part of Regular Coursework. In the case of an allegation of academic misconduct associated with **activities not a part of regular coursework** (e.g., an allegation of cheating on a comprehensive examination or academic misconduct in connection with a graduate thesis project), if after talking with the student, faculty member(s) finds the student is responsible for misconduct the faculty should:

- Report the violation using this form (or via deanofstudents@mines.edu) within five business days of meeting with the student (as outlined above – see 3.1). The reporting form will collect information on the student(s), violation(s), and other necessary course information. (e.g. cheating, plagiarism, etc.).The Dean of Students Office will communicate the resolution in writing to the student, the faculty member(s), appropriate members of Academic Affairs, the Office of Graduate Studies (if applicable), the student's advisor, and any additional appropriate parties including Athletics, course coordinators, or the Registrar's Office. The Dean of Students will keep official records on all students with academic misconduct violations.
- Assign an outcome to the activity that constitutes failure. If appropriate, the student's advisor may also assign a grade of PRU (unsatisfactory progress) for research credits in which the student is enrolled. Regular institutional procedures resulting from either of these outcomes are then followed. Faculty members may impose a lesser penalty if the circumstances warrant, however, the typical sanction is failure.

3.3.3 Research Activities. In the case of an allegation of academic misconduct associated with **research activities**, investigation and resolution of the misconduct is governed by the institution's Research Integrity Policy. The Research Integrity Policy is available as section 10.3 of the Faculty Handbook. If, after talking with the student, the faculty member feels the student is responsible for misconduct of this type, the faculty member should proceed as indicted in the Research Integrity Policy. If appropriate, the student's advisor may also assign a grade of PRU for research credits in which the student is enrolled. Regular institutional procedures resulting from this grade assignment are then followed.

**3.4 Student Reporting**. Students who suspect other students of academic misconduct should report the matter to the appropriate faculty member, the appropriate department head/program director, the Dean of Undergraduate Studies, the Dean of Graduate Studies, or the Dean of Students. The information is then provided to the faculty member concerned.

## 4.0 STUDENT ACADEMIC MISCONDUCT APPEAL PROCESS

### 4.1 Purpose

A student may appeal a decision within certain timelines and under specific criteria. For all charges of academic misconduct, upon notification of a finding of academic misconduct and the

associated penalties, the student may appeal the decision of the faculty member.

An appeal is not a second hearing of the case, but rather it is a review of the procedures followed and information presented to determine if the process provided was in accordance with the policy or if the decision was unsupported by the evidence, as set forth below.

This appeal process governs all requests for appeal related to violations of the Academic Integrity/Misconduct Policy. Grade appeals, residency appeals, student conduct appeals, and appeals related to research misconduct are handled through separate processes. Please see the Mines Policy webpage for more information on those processes.

**4.2 Grounds for Appeal**

An appeal request will be considered only if it includes the specific grounds for an appeal and the rationale that support the selected grounds. The three items listed below are the only acceptable grounds for an appeal:

- **Due Process**. To determine whether the meeting with the faculty member and the process followed was conducted fairly and in conformity with the prescribed procedures. Any procedural errors must have been so substantial as to effectively deny the student a reasonable opportunity to prepare and present information about an alleged policy violation. The student should be able to show that there would have been a different outcome if the procedural error had not occurred. Minor deviations that do not materially affect the outcome are not a basis for sustaining an appeal.
- **New Information**. To consider information or other relevant facts sufficient to alter a decision because such information was not known by the student at the time of the original conduct meeting with the faculty member.
- **Unsupported Decision**. To determine whether the decision reached by the faculty member was supported using the preponderance of evidence standard to establish that a violation of the policy occurred. This ground for appeal requires the student to show that no reasonable person could have determined that the student was responsible or could have imposed the sanctioned issued based on the available evidence.

**4.3 Submitting an Appeal Request**

Decisions reached by a faculty member may be appealed by the student. A student may file an appeal by completing a Student Conduct Appeal form and submitting it to the Dean of Students Office by the date stated on the original decision letter (typically seven business days). This form is available online at https://www.mines.edu/policy-library/student/ and in person at the Student Life Office. It is the student's obligation to complete the form in its entirety and provide any and all materials that they wish to have considered at the time of the appeal submission. Incomplete form, late submissions, or revised requests will not be accepted. If the student's appeal request is not received by the designated deadline, the decision of the faculty member is final and no further appeal will be permitted.

**4.3.1 Appeal Request Review**. Once an appeal request is received, it is forwarded to the Dean of Students. Within five business days, the Dean of Students will review the request to determine if the acceptable grounds for an appeal have been met, if the appeal has been timely filed, and if the request is complete. After review of the request, the Dean of Students will take one of the following actions:

a. Accept the Appeal Request – See section 4.3.2 below
b. Deny the Appeal Request – The Dean of Students will notify the student that the appeal has been denied and the basis for the denial. An appeal that does not set forth sufficient grounds for appeal (as described in section 2.0 above) will be denied. In such cases, the original decision of the faculty member is considered binding upon all involved and the matter will be considered closed unless the student can provide evidence that the Dean of Students made an arbitrary decision without fully considering the information presented. If that is the case, the student requesting the appeal must notify the associate vice president of Student Life in writing within two business days and request that the appeal be reviewed again by the associate vice president of Student Life. The associate vice president of Student Life will review the request within two business days. The associate vice president of Student Life will either accept the appeal request (see section 3.2) or deny the appeal request. If the associate vice president of Student Life denies the appeal request, the decision is final and considered binding upon all involved.

**4.3.2 Accepted Appeal.** Once the appeal request has been accepted by the Dean of Students (or associate vice president of Student Life), the Dean of Students will proceed as follows:

a. Notify the student and the faculty member that the appeal has been accepted and the appeal will proceed.
b. Schedule a date and time for the appeal meeting to be held.
c. Provide the student and faculty member with an overview of the appeal process and allow them to submit any additional information related to the academic misconduct charge that they would like to be included in the appeal meeting.
d. Forward the appeal and all supporting documents to the participating members of the Student Conduct Appeals Board.

**4.4 Student Conduct Appeals Board**

The Student Conduct Appeals Board ("Board") consists of 16 members of the campus community, including six students, six faculty, and four staff, plus the Dean of Students as the chair. A minimum of three Board members (including one student and one faculty member) are required for all appeal meetings.

Upon acceptance of an appeal, the list of the members of the Student Conduct Appeals Board will be provided to the student and the faculty member. Both the student and the faculty member

may each request the removal of one of the Board members' from participating in the appeal meeting. Upon receipt of such requests, the Dean of Students will remove the potential member from participating.

Once an appeal request is accepted and the appeal meeting scheduled, non-excluded Board members will be contacted and invited to participate at the appeal meeting. Appeals Board members have an affirmative obligation to excuse themselves if they have a conflict of interest. The Dean of Students will provide participating Board members with all pertinent information regarding the incident and appeal, including but not limited to the student's education records, the appeal request, and other information submitted by the student and the faculty member.

**4.5 Appeal Meeting**

The student and the faculty member will meet with the participating Student Conduct Appeals Board members during the appeal meeting. Both the student and the faculty member will be allowed to provide a brief statement and then answer questions from the Appeals Board members. The student and faculty member will not be permitted to question one another. All questioning will be done by the Board members. The Board members may, at their discretion, meet with any appropriate witnesses during the meeting. After all questioning has occurred, the student and faculty member will be excused.

**4.5.1 Recordings**. If requested by the student or faculty member, one verbatim record, such as a recording, will be made. This recording shall be the property of Mines. If such a recording is made, a student wishing to obtain a copy of the recording must submit a request to the Dean of Students. This may be done via mail, email, or in person. Once the request has been received, the Dean of Students will provide both parties with a copy of the recording.

**4.5.2 Advisor.** The appeal meeting is an internal university judicial matter. Students are allowed to have one individual advisor (parent, lawyer, friend etc.) in the room during the appeal meeting. The advisor is not allowed to speak on the student's behalf or address the committee during the appeal meeting. He/she is only allowed to hear the information being provided to the committee, confer with the student, and offer the student advice. This individual is not permitted to represent the student or speak on the student's behalf during the appeal meeting.

**4.6 Pending Action**

Throughout the entire appeal process, and while the decision of the Dean of Students or the Student Conduct Appeals Committee is pending, the student must continue to comply with all conditions of the original decision made by the faculty member. Unless otherwise specified in the original written notification of suspension, a student may continue to attend classes while the appeal is pending.

**4.7 Decision**

At the conclusion of the appeal meeting, the Student Conduct Appeals Board will make one of the following decisions:

1. Reverse the decision of the faculty member and withdraw the charge from the student's record.
2. Affirm the decision of the faculty member and uphold the sanction(s).
3. Forward the case to the Office of Academic Affairs for further consideration: the Student Conduct Appeals Board believes that additional matters implicated in the appeal should be reviewed and considered which could include increasing or decreasing the sanctions imposed or addressing additional issues that arose through the appeal process. Recommendations for appropriate sanctions should be made by the Student Appeals Committee to the Office of Academic Affairs. The additional review and consideration will be conducted by the Dean of Undergraduate Studies or Dean of Graduate Studies, depending on the academic standing of the student requesting the appeal. The Office of Academic Affairs staff member will make a final decision that will be communicated to the student within 10 business days.

The decision made will be communicated to the student and faculty member within 24 hours of the conclusion of the appeal meeting. The decision issued by the Student Conduct Appeals Board or the Office of Academic Affairs (in matters that are forwarded for further consideration) is final and shall be considered binding upon all involved, to which no additional appeals are permitted.

*For the most up-to-date version of this procedure and appeal request forms, please see the* student section of the policy website*.*

# POLICY PROHIBITING UNLAWFUL DISCRIMINATION

**1.0. BACKGROUND AND PURPOSE**

Colorado School of Mines ("Mines") is committed to inclusivity and access for all persons and strives to create learning and workplace environments that exclude all forms of unlawful discrimination, harassment, and retaliation. Mines' commitment to nondiscrimination, affirmative action, equal opportunity, and equal access is reflected in the administration of its policies, procedures, programs, and activities, as well as its efforts to achieve a diverse student body and workforce.

As part of this commitment, the Board of Trustees of Colorado School of Mines promulgates this policy pursuant to the authority conferred by §23-41-104(1), C.R.S., and in accordance with applicable federal and Colorado civil rights laws.

**2.0 POLICY STATEMENT**

Mines prohibits discrimination and harassment on the basis of age, ancestry, creed, marital status, race, color, ethnicity, religion, national origin, sex, gender, gender identity, gender expression, disability, sexual orientation, genetic information, veteran status, or military service. This prohibition applies to all students, employees, contractors, visitors, and volunteers.

Mines will not tolerate retaliation against Mines community members for filing complaints regarding or implicating any of these protected statuses, or otherwise participating in investigations regarding such complaints.

It is a violation of this policy to intentionally submit a false complaint or file a complaint that is not made in good faith or to provide materially false or misleading information during an investigation.

**3.0 RESPONSIBILITIES**

The Board of Trustees directs the president, or the president's delegates to develop, manage, and maintain appropriate procedures and resources to implement this policy.

**4.0 COMPLIANCE/ENFORCEMENT**

Violators of this policy will be subject to disciplinary action, up to and including termination of employment, expulsion, and termination of contractual relationships with Mines.

**5.0 EXCLUSIONS/DISCLAIMER**

No one filing a complaint under this policy will be permitted to simultaneously file a grievance under the State of Colorado Personnel Board Rules or Colorado School of Mines Faculty Handbook against the same individual and arising out of the same event(s).

**6.0 RESOURCES OR ATTACHMENTS**

- Equal Pay Act of 1963
- Titles IV, VI, and VII of the Civil Rights Act of 1964
- Title IX of the Education Amendments of 1972
- Rehabilitation Act of 1973 (sections 503 and 504)
- Vietnam Era Veterans Readjustment Assistance Act
- Age Discrimination Act
- Pregnancy Discrimination Act
- Age Discrimination in Employment Act of 1976
- Americans with Disabilities Act (as amended)
- Executive Order 11246
- Jeanne Clery Disclosure of Campus Security Policy and Crime Statistics Act of 1991
- Uniform Services Employment and Reemployment Act
- Violence Against Women Act of 1994
- Violence Against Women Reauthorization Act of 2013
- Colorado Anti-Discrimination Act
- Statement of Equal Opportunity, Access, and Nondiscrimination (https://www.mines.edu/equal-opportunity/)
- Title IX Office website: https://www.mines.edu/title-ix/
- Human Resources website: https://www.mines.edu/human-resources/

KEY WORDS
Discrimination, harassment, age, ancestry, creed, marital status, race, color, ethnicity, religion, national origin, sex, gender, gender identity, gender expression, disability, sexual orientation, genetic information, veteran status, military service

**HISTORY & REVIEW CYCLE**

***For a complete policy statement*** *and the most up-to-date procedures, please see the* policy website*. Promulgated by the Mines Board of Trustees on March 13, 1992. Amended by the Mines Board of Trustees on June 10, 1999; June 22, 2000; June 7, 2003; August 14, 2007; August 29, 2014; February 8, 2019; and August 14, 2020.*

## Alcohol and Other Drugs Education and Prevention Policy

In compliance with the federal government's Drug Free Schools and Communities Act, there are community standards and potential consequences at Colorado School of Mines pertaining to the illegal use of alcohol or drugs. The unlawful possession, use, or distribution of illicit drugs and the unlawful or unauthorized use of alcohol by employees and students at Mines will result in disciplinary action consistent with School policies, and local, state, and federal laws.

While Colorado's constitution allows for specific legal use, possession, and growing of marijuana under certain circumstances, because of Mines' status as a federal contractor and grant recipient and because marijuana use is still prohibited under federal law, the use, possession, and growing of marijuana on campus is prohibited. Student use of alcohol and other drugs (including marijuana) that results in an impaired ability to perform academically, or behavior that violates the Code of Conduct constitutes a violation of this policy.

For more information, or for further policy details, please see the Alcohol and Other Drugs Education and Prevention Policy and the Colorado Drug Law Summary in the Policy Library, student section. Also see the Residence Life Policies and the Annual Campus Security and Fire Safety Report for more on programming and requirements.

## Electronic Communications (Email) Policy

**1.0 BACKGROUND AND PURPOSE**

Communication to students at Colorado School of Mines (Mines) is an important element of the official business of the university. It is vital that Mines have an efficient and workable means of getting important and timely information to students. Examples of communications that require timely distribution include information from Fiscal Services, the Registrar's Office, or other offices on campus that need to deliver official and time-sensitive information to students. (Please note that emergency communications may occur in various forms based on the specific circumstances).

Electronic communication through email and Trailhead Portal announcements provides a rapid, efficient, and effective form of communication. Reliance on electronic communication has become the accepted norm within the Mines community. Additionally, utilizing electronic communications is consistent with encouraging a more environmentally conscious means of doing business and encouraging continued stewardship of scarce resources. Because of the widespread use and acceptance of electronic communication, Mines is adopting the following policy regarding electronic communications with students.

**2.0 POLICY**

It is the policy of Colorado School of Mines that official university-related communications with students will be sent via Mines' internal email system or via campus or targeted Trailhead announcements. All students will be assigned a Mines email address and are expected to periodically check their Mines assigned email as well as their Trailhead portal page. It is also expected that email sent to students will be read in a timely manner. Communications sent via email to students will be considered to have been received and read by the intended recipients.

*For a complete policy statement and associated procedures please see the* policy website*,* information technology section. ***The policy website shall be considered the official & controlling Mines' policy.*** Nothing in the procedures should be construed as prohibiting university-related communications being sent via traditional means. Use of paper-based communication may be necessary under certain circumstances or may be more appropriate to certain circumstances. Examples of such communications could include, but not be limited to disciplinary notices, fiscal services communications, graduation information, and so forth.

Questions about this policy may be directed to either of the following: Registrar's Office at 303-273-3200 or registrar@mines.edu; or

Computing, Communications & Information Technologies (CCIT) at 303-273-3431 or complete a request form at the Mines Help Center.

## Student Complaint Process

Students are consumers of services offered as part of their academic and co-curricular experience at Colorado School of Mines. If a student needs to make a complaint, specific or general, about their experience at Mines, he or she should contact the Office of the Dean of Students at 303-273-3288. If the issue is related to discrimination, sexual harassment, or sexual violence, there are specific procedures that will be followed (these are noted and linked in this section, or contact the Director, Title IX & Equity, 303-273-2558. Additional contacts listed in the Title IX section below.) For all other concerns, the student should begin with the Dean's Office if interested in making any complaint. All complaints, as well as the interests of all involved parties, will be considered with fairness, impartiality, and promptness while a complaint is being researched and/or investigated by the school.

## Access to Student Records

The Family Educational Rights and Privacy Act (FERPA) gives students who reach the age of 18 or who attend a postsecondary institution the right to inspect, review, and request amendment their own Education Records. At the postsecondary level, parents have no inherent rights to inspect, review, or request amendment to a student's Education Records. Mines will provide an annual notice of rights under FERPA to students currently attending the University. Mines may disclose information contained in a student's Education Record as set forth in the Mines Notice of Student Rights Under the Family Educational Rights and Privacy Act of 1974. Mines will securely destroy Education Records that are no longer required to be maintained using a method that renders the content irretrievable and illegible.

Contact information for FERPA complaints:

Family Policy Compliance Office
U.S. Department of Education
400 Maryland Avenue, SW
Washington, D. C. 20202-4605

**Directory Information.** The school maintains lists of information which may be considered directory information as defined by the regulations. This information includes name, current and permanent addresses and phone numbers, date of birth, major field of study, dates of attendance, part- or full-time status, degrees awarded, last school attended, participation in officially recognized activities and sports, class, academic honors, university email address, and photo including student ID picture. Students who desire that this information not be printed or released must so inform the registrar before the end of the first two weeks of the fall semester for which the student is registered. Information will be withheld for the entire academic year unless the student changes this request. The student's signature is required to make any changes for the current academic year. The request must be renewed each fall term for the upcoming year. The following student records are maintained by Colorado School of Mines at the various offices listed below:

1. General Records: Registrar and Graduate Dean
2. Transcript of Grades: Registrar
3. Computer Grade Lists: Registrar
4. Encumbrance List: Controller and Registrar
5. Academic Probation/Suspension List: Dean of Students and Graduate Dean
6. Advisor File: Academic Advisor
7. Option/Advisor/Enrolled/ Minority/Foreign List: Registrar, Dean of Students, and Graduate Dean
8. Externally Generated SAT/GRE Score Lists: Graduate Dean
9. Financial Aid File: Financial Aid (closed records)
10. Medical History File: School Physician (closed records)

**Access to Records by Other Parties.** Colorado School of Mines will not permit access to student records by persons outside the school except as follows:

1. In the case of open record information as specified in the section under Directory Information.
2. To those people specifically designated by the student. Examples would include request for transcript to be sent to graduate school or prospective employer.
3. Information required by a state or federal agency for the purpose of establishing eligibility for financial aid.
4. Accreditation agencies during their on-campus review.
5. In compliance with a judicial order or lawfully issued subpoena after the student has been notified of the intended compliance.
6. Any institutional information for statistical purposes which is not identifiable with a particular student.
7. In compliance with any applicable statue now in effect or later enacted. Each individual record (general, transcript, advisor, and medical) will include a log of those persons not employed by Colorado School of Mines who have requested or obtained access to the student record and the legitimate interest that the person has in making the request.

The school discloses education records without a student's prior written consent under the FERPA exception for disclosure to school officials with legitimate educational interests. A school official is a person employed by the school in an administrative, supervisory, academic or research, or support staff position (including law enforcement unit personnel and health staff); a person or company with whom the school has contracted as its agent to provide a service instead of using school employees or officials (such as an attorney, auditor, or collection agent); a person serving on the Board of Trustees; or a student serving on an official committee, such as a disciplinary or grievance committee, or assisting another school official in performing his or her tasks.

A school official has a legitimate educational interest if the official needs to review an education record in order to fulfill his or her professional responsibilities for the school.

See also https://www.mines.edu/policy-library/ferpa-policy/.

## Posthumous Degree Awards

The faculty may recognize the accomplishments of students who have died while pursuing their educational goals. If it is reasonable to expect that the student would have completed his or her degree requirements, the faculty may award a baccalaureate or graduate degree that is in all ways identical to the degree the student was pursuing. Alternatively, the faculty may award a posthumous BS, MS, or PhD to commemorate students who distinguished themselves while at Mines by bringing honor to the school and its traditions.

Consideration for either of these degrees begins with a petition to the Faculty Senate from an academic department or degree granting unit. The petition should identify the degree sought. In the event that the degree-granting unit is seeking a conventional degree award, the petition should include evidence of the reasonable expectations that the student would have completed his or her degree requirements. For a baccalaureate, such evidence could consist of, but is not limited to:

- The student was a senior in the final semester of coursework,
- The student was enrolled in courses that would have completed the degree requirements at the time of death
- The student would have passed the courses with an acceptable grade, and would likely have fulfilled the requirements of the degree.

For a Graduate Degree:

- For graduate degrees not requiring a research product, the student was enrolled in courses that would have completed the degree requirements at the time of death, would have passed the courses with an acceptable grade, and would likely have fulfilled the requirements of the degree.
- For graduate degrees requiring a research product, the student had completed all course and mastery requirements pursuant to the degree and was near completion of the dissertation or thesis, and the student's committee found the work to be substantial and worthy of the degree.

The requirement that there be a reasonable expectation of degree completion should be interpreted liberally and weight should be given to the judgment of the departmental representative(s) supporting the petition.

In the event that the degree being sought is a posthumous BS, MS, or PhD, the petition should include evidence that the student conducted himself or herself in the best tradition of a Mines' graduate and is therefore deserving of that honor.

## Equal Opportunity, Equal Access, and Affirmative Action

The institution's Statement of Equal Opportunity and Equal Access to Educational Programs and associated staff contacts can be found in the Welcome Section of this Catalog as well as on the policy webpage. Colorado School of Mines maintains an affirmative action plan, which is available at the Arthur Lakes Library, the Dean of Students Office, and the Office of Human Resources.

## Office of Institutional Equity and Title IX

Pursuant to Title IX of the Education Amendments of 1972, 20 U.S.C. § 1681, and 34 CFR Part 106, Mines does not discriminate on the basis of sex in any of its education programs or activities, including admissions and employment. All inquiries about the application of Title IX or Part 106 may be directed to Mines Title IX Coordinator or the Assistant Secretary of Education, U.S. Department of Education, or both:

Mines Title IX Coordinator is Carole Goddard.
Office: Title IX House, 1706 Illinois Street
Email: titleix@mines.edu
Phone: 303-273-3260
Website: https://www.mines.edu/institutional-equity-title-ix/

The Policy Prohibiting Sexual Harassment, Sexual Assault, and Interpersonal Violence can be found here: https://www.mines.edu/policy-library/policy-prohibiting-sexual-misconduct-discrimination-and-retaliation/

The Procedure to Resolve Complaints of Sexual Harassment, Sexual Assault, and Interpersonal Violence can be found here: https://www.mines.edu/policy-library/procedure-a-resolution-for-complaints-of-sexual-misconduct-under-title-ix/.

Additionally, student complaints of discrimination, harassment, and retaliation on the basis of a protected class (race, color, religion or creed, sex [including pregnancy, childbirth, related medical conditions, sexual orientation, gender identity, and gender expression], marital status, ethnicity, national origin, age, disability, genetic information, ancestry, and veteran status or military service), are managed through the Office of Equity and Title IX. The Policy Prohibiting Unlawful Discrimination is listed above and can also be found here: https://www.mines.edu/policy-library/procedure-b-resolution-for-complaints-of-sexual-misconduct-discrimination-and-retaliation/.

## SpeakUP@Mines

Students and employees have an additional anonymous channel for reporting concerns through the Whistleblower Policy and the SpeakUP@Mines program.

## Consumer Information – Your Right to Know

As a prospective or continuing student at Colorado School of Mines, you have a right to certain information that the university is required by law to provide. Much of that information is safety related or financial in nature, but other broad categories are included such as graduation rates, athletics, and the various costs associated with attending Mines.

Current federal regulations require that institutions of higher education disclose such information and make it readily available to current and prospective students. A new provision in the Higher Education Amendments of 1998 requires institutions to provide a list of the information to which students are entitled with instructions on how they may obtain it. A paper copy of all the information can be found in the Compliance and Policy Office in Guggenheim Hall.

More information can be found on the Financial Aid website.

# Directory of the School

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