Mechanical Engineering

Degrees Offered

- Master of Science (Mechanical Engineering)
- Doctor of Philosophy (Mechanical Engineering)

Program Overview

The Mechanical Engineering Department offers the Master of Science and Doctor of Philosophy degrees in Mechanical Engineering. The program demands academic rigor and depth yet also addresses real-world engineering problems. The department has four broad divisions of research activity that stem from core fields in Mechanical Engineering: (1) Biomechanics, (2) Thermal-Fluid Systems, (3) Solid Mechanics and Materials, and (4) Robotics, Automation, and Design. In many cases, individual research projects encompass more than one research area and elements from other disciplines.

Biomechanics focuses on the application of engineering principles to the musculoskeletal system and other connective tissues. Research activities include experimental, computational, and theoretical approaches with applications in the areas of rehabilitation engineering, computer-assisted surgery and medical robotics, patient-specific biomechanical modeling, intelligent prosthetics and implants, and bioinstrumentation. The Biomechanics group has strong research ties with other campus departments, the local medical community, and industry partners.

Robotics, Automation, and Design merges research from multiple areas of science and engineering. Topics include the design of robotic and automation system hardware and software, particularly for tasks that require some level of autonomy, intelligence, self-prognostics and decision making. Such capabilities are built upon integrated mechatronic systems that enable pro-active system responses to its environment and current state. These capabilities are applied in applications such as advanced robotics and manufacturing systems. Research in this division explores the science underlying the design process, implementation of mechanical and control systems to enable autonomy, and innovative computational analysis for automation, intelligence, and systems optimization.

Solid Mechanics and Materials develops novel computational and experimental solutions for problems in the mechanical behavior of advanced materials. Research in the division spans length scales from nanometer to kilometer, and includes investigations of microstructural effects on mechanical behavior, nanomechanics, granular mechanics, and continuum mechanics. Material-behavior models span length scales from the nano- and micro-scale, to the meso- and macro-scale. Much of the research is computational in nature using advanced computational methods such as molecular dynamics, finite-element, boundary-element and discrete-element methods. Strong ties exist between this group and the campus communities of applied mathematics, chemical engineering, materials science, metallurgy, and physics.

Thermal-Fluid Systems incorporates a wide array of multidisciplinary applications such as advanced energy conversion and storage, multi-phase fluid flows, materials processing, combustion, alternative fuels, and renewable energy. Research in thermal-fluid systems integrates the disciplines of thermodynamics, heat transfer, fluid mechanics, transport phenomena, chemical engineering, and materials science towards solving problems and making advances through experiments and computational modeling in the broad areas of energy conversion, fluid mechanics, and thermal transport. Research projects in this area specialize in some aspect of mechanical engineering but often have a strong interdisciplinary component in related fields such as Materials Science and Chemical Engineering.

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’ Combined Undergraduate / Graduate Degree Program

The ME Department will allow students enrolled in the combined BS-Mechanical Engineering / MS-Mechanical Engineering Non-Thesis program to double count up to 6 course credits from their undergraduate ME degree requirements. This program enables students to begin graduate coursework while still finishing their undergraduate degree requirements. Students enrolled in Mines’ combined undergraduate/graduate program (meaning uninterrupted registration from the time the student earns a Mines undergraduate degree to the time the student begins a Mines graduate degree) may double count up to six hours of credits of MEGN 500-level courses, which were used in fulfilling the requirements of their undergraduate degree at Mines, towards their non-thesis graduate program. These courses must have been passed with a “B-” or better and meet all other University, Department, Division, and Program requirements for graduate credit.

Prerequisites

Requirements for Admissions: The minimum requirements for admission into the MS and PhD degrees in Mechanical Engineering are:

- a baccalaureate degree in engineering, computer science, a physical science, or mathematics with a minimum grade-point average of 3.0;
- Graduate Record Examination (Quantitative Reasoning) section score of 160 or higher. Applicants from an engineering program at CSM are not required to submit GRE scores;
- TOEFL score of 79 or higher (or 550 paper-based or 213 computer-based) for applicants whose native language is not English.

Program Requirements

Admitted Students: The Mechanical Engineering graduate admissions committee may require that an admitted student complete undergraduate remedial coursework to overcome technical deficiencies. Such coursework may not count toward the graduate degree. The committee will decide whether to recommend regular or provisional admission, and may ask the applicant to come to campus for an interview.

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 into the Mechanical Engineering Department. Approval from the Advisor and/or Thesis Committee and ME Department Head will be required 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 credit hours 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 course work and research completed for that degree.

400-level Courses: As stipulated by the CSM Graduate School, students may apply toward graduate degree requirements a maximum of nine (9.0) semester hours of department-approved 400-level course work.

Master of Science Degree Requirements

The MS degree in Mechanical Engineering requires 30 credit hours. Requirements for the MS thesis option are 24 credit hours of coursework and 6 credit hours of thesis research. The MS non-thesis option requires 30 credit hours of coursework. All MS students must complete nine credit hours of course work in one research division by selecting three courses listed under the Research Division Courses.

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 Thesis Degree**

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Hours</th>
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<tbody>
<tr>
<td>MEGN502</td>
<td>ADVANCED ENGINEERING ANALYSIS</td>
<td>3.0</td>
</tr>
<tr>
<td>MEGN503</td>
<td>GRADUATE SEMINAR Enrollment required every fall and spring semester</td>
<td>0.0</td>
</tr>
<tr>
<td>RESEARCH</td>
<td>Courses from one Research Division List</td>
<td>9.0</td>
</tr>
<tr>
<td>TECHNICAL</td>
<td>Technical Electives Courses approved by Advisor/Thesis Committee</td>
<td>9.0</td>
</tr>
<tr>
<td>ELECTIVES</td>
<td>Any 400-level or above ME Course</td>
<td>3.0</td>
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<tr>
<td>MEGN707</td>
<td>GRADUATE THESIS / DISSERTATION</td>
<td>6.0</td>
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<td>RESEARCH CREDIT</td>
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<td></td>
<td><strong>Total Semester Hrs</strong></td>
<td><strong>30.0</strong></td>
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**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 to his Advisor and Thesis Committee.

**MS Non-Thesis Degree**

<table>
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<tbody>
<tr>
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</tr>
<tr>
<td>RESEARCH</td>
<td>Course from one Research Division List</td>
<td>9.0</td>
</tr>
<tr>
<td>TECHNICAL</td>
<td>Technical Electives Courses must be approved by Advisor.</td>
<td>9.0</td>
</tr>
<tr>
<td>ELECTIVES</td>
<td>Any ME 400-level or above course</td>
<td>9.0</td>
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<td></td>
<td><strong>Total Semester Hrs</strong></td>
<td><strong>30.0</strong></td>
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**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.

**Doctor of Philosophy Degree Requirements**

The PhD degree in Mechanical Engineering requires 72 credit hours of course work and research credits. A minimum of 36 credit hours of course work and 30 credit hours of research credits must be completed. A minimum of 12 of the 36 credit hours of required coursework must be taken at Colorado School of Mines. All students must complete nine credit hours of course work within one research area by selecting 3 courses listed under the Research Division Courses.

<table>
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<td>ADVANCED ENGINEERING ANALYSIS</td>
<td>3.0</td>
</tr>
<tr>
<td>MEGN503</td>
<td>GRADUATE SEMINAR Enrollment required every fall and spring semester</td>
<td>0.0</td>
</tr>
<tr>
<td>RESEARCH</td>
<td>Courses from one Research Division List</td>
<td>9.0</td>
</tr>
<tr>
<td>TECHNICAL</td>
<td>Technical Electives Must be approved by the Advisor/Thesis Committee.</td>
<td>24.0</td>
</tr>
<tr>
<td>ELECTIVES</td>
<td>GRADUATE THESIS / DISSERTATION</td>
<td>30.0</td>
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<tr>
<td></td>
<td>RESEARCH CREDIT</td>
<td></td>
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<tr>
<td></td>
<td><strong>Total CREDITS</strong></td>
<td><strong>72.0</strong></td>
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**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 ME faculty has adopted a PhD timeline that outlines milestones students must reach on a semester-by-semester basis. These milestones include selecting a permanent Advisor, establishing a thesis committee, completing the qualifying exam, presenting a research proposal, submitting appropriate graduation forms to move to admission to candidacy, a preliminary defense, and a final dissertation defense. Additional milestones also include journal publications requirements.

**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. The PhD qualifying exam will be administered at a specific date during every semester by each research division independently. Each research division will appoint a Qualifying Exam chair, who oversees the process and ensures that the exam is administered fairly. Students must take the exam by no later than the end of their third semester in the Mechanical Engineering PhD program. If the student fails the exam on their first attempt, they must retake the exam in the following semester with a maximum of two attempts to pass. One-semester extensions may be granted upon request to students who are enrolled as part-time or with non-ME backgrounds.

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.

A written exam not to exceed 4.5 hours will be administered which will be divided into no more than five topical areas related to the research division, with topics announced in advance of the exam. The students will choose three topical areas to answer. Research divisions are encouraged...
to choose topical areas that relate to foundational undergraduate material linked to material in the core graduate courses required by that research division. Upon completion of the written exam, students will choose one paper out of a list of papers established by the research division faculty. Students will be given two weeks to write a two-page critical review of the paper which discusses possible extensions of the research.

Students, with a satisfactory performance on the written exam, will participate in an oral exam not to exceed two hours. The oral exam will be conducted by the qualifying exam committee and the student's Advisor. The research division will specify the format of the exam in advance of the exam.

Exam results of Pass, Conditional Pass or Fail will be provided to the student in a timely manner by the exam committee. A Conditional Pass will require the student to take a remedial plan.

Research Proposal: After passing the Qualifying Examination, the PhD student will prepare a written Thesis Proposal and present it formally to the student's graduate committee and other interested faculty.

Degree Audit and Admission to Candidacy: PhD students must complete the Degree Audit form (http://gradschool.mines.edu/Degree-Audit) by the posted deadlines and the Admission to Candidacy form (http://gradschool.mines.edu/Admission-to-Candidacy-form) by the first day of classes in 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 into the 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; and
- be admitted into full candidacy for the degree.

Preliminary Defense: Prior to the final thesis defense, the PhD student will make an oral presentation to the student's graduate committee to summarize research accomplishments and work remaining.

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.

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.

RESEARCH DIVISION COURSES

BIOMECHANIC COURSES

MEGN514 CONTINUUM MECHANICS
MEGN531 PROSTHETIC AND IMPLANT ENGINEERING
MEGN532 EXPERIMENTAL METHODS IN BIOMECHANICS
MEGN535 MODELING AND SIMULATION OF HUMAN MOVEMENT
MEGN536 COMPUTATIONAL BIOMECHANICS
MEGN540 MECHATRONICS

ROBOTICS AND AUTOMATION

MEGN540 MECHATRONICS
MEGN544 ROBOT MECHANICS: KINEMATICS, DYNAMICS, AND CONTROL
MEGN545 ADVANCED ROBOT CONTROL
MEGN587 NONLINEAR OPTIMIZATION
MEGN588 INTEGER OPTIMIZATION

SOLID MECHANICS AND MATERIALS

MEGN511 FATIGUE AND FRACTURE
MEGN512 ADVANCED ENGINEERING VIBRATION
MEGN514 CONTINUUM MECHANICS
MEGN515 COMPUTATIONAL MECHANICS
MEGN517 INELASTIC CONSTITUTIVE RELATIONS
MEGN598 MICROMECHANICS/HOMOGENIZATION

THERMAL-FLUID SYSTEMS

MEGN551 ADVANCED FLUID MECHANICS
MEGN552 VISCOS FLOW AND BOUNDARY LAYERS
MEGN561 ADVANCED ENGINEERING THERMODYNAMICS
MEGN566 COMBUSTION
MEGN571 ADVANCED HEAT TRANSFER

MEGN501. ADVANCED ENGINEERING MEASUREMENTS. 3.0 Semester Hrs.
Equivalent with EGGN501.
(i) 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: EGGN250, EENG281 or equivalent, and MATH323 or equivalent; graduate student status. 3 hours lecture, 1 hour lab; 3 semester hours.

MEGN502. ADVANCED ENGINEERING ANALYSIS. 3.0 Semester Hrs.
Equivalent with EGGN502.
(i) 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. Prerequisite: This is an introductory graduate class. The student must have a solid understanding of linear algebra, calculus, ordinary differential equations, and Fourier theory. 3 hours lecture.

MEGN503. GRADUATE SEMINAR. 0.0 Semester Hrs.
Equivalent with EGGN504M.
(i, ii) 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-economic 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. Prerequisite: Graduate standing. 1 hour per week; 0 semester hours. Course is repeatable, but no coursework credit is awarded.
MEGN510. SOLID MECHANICS OF MATERIALS. 3.0 Semester Hrs.
Equivalent with EGGN543.
(I) Introduction to the algebra of vectors and tensors; coordinate transformations; general theories of stress and strain; principal stresses and strains; octahedral stresses; Hooke’s Law introduction to the mathematical theory of elasticity and to energy methods; failure theories for yield and fracture. Prerequisite: CEEN311 or equivalent, MATH225 or equivalent. 3 hours lecture; 3 semester hours.

MEGN511. FATIGUE AND FRACTURE. 3.0 Semester Hrs.
Equivalent with EGGN532, MTGN545,
(I) Basic fracture mechanics as applied to engineering materials. S-N curves, the Goodman diagram, stress concentrations and residual stress effects, effect of material properties on mechanisms of crack propagation. Prerequisite: none. 3 hours lecture; 3 semester hours. Fall semesters, odd numbered years.

MEGN512. ADVANCED ENGINEERING VIBRATION. 3.0 Semester Hrs.
Equivalent with EGGN546.
Vibration theory as applied to single- and multi-degree-of freedom systems. Free and forced vibrations to different types of loading-harmonic, impulse, periodic and general. Natural frequencies. Role of Damping. Importance of resonance. Modal superposition method. Prerequisite: MEGN315, 3 hours lecture; 3 semester hours.

MEGN513. KINETIC PHENOMENA IN MATERIALS. 3.0 Semester Hrs.
Equivalent with EGGN555, MLGN511,
(I) Linear irreversible thermodynamics, dorce-flux couplings, diffusion, crystalline materials, amorphous materials, defect kinetics in crystalline materials, interface kinetics, morphological evolution of interfaces, nucleation theory, crystal growth, coarsening phenomena and grain growth, solidification, spinodal decomposition. Prerequisites: MATH225: Differential equations (or equivalent), MLGN504/MTGN555/CBEN509: Thermodynamics (or its equivalent).

MEGN514. CONTINUUM MECHANICS. 3.0 Semester Hrs.
(I) 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). 3 hours lecture, 3 semester hours.

MEGN515. COMPUTATIONAL MECHANICS. 3.0 Semester Hrs.
(I) A graduate course in computational mechanics with an emphasis on 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-dimensional models of crystal mechanics and phenomenological thermodynamic internal variable theory. We also discuss ties between models and state of the art experimental mechanics, including in-situ diffraction. We will cover both theory and numerical implementation strategies for the topics. Thus, students will gain experience interpreting, formulating, deriving, and implementing three-dimensional constitutive laws and crystal mechanics models. We will introduce many topics rather than focusing on a few such that students have a foot-in to dive deeper on their own, as they will do in the project. Prerequisites: MEGN514. 3 hours lecture, 3 semester hours.

MEGN520. BOUNDARY ELEMENT METHODS. 3.0 Semester Hrs.
Equivalent with EGGN545.
(I) Development of the fundamental theory of the boundary element method with applications in elasticity, heat transfer, diffusion, and wave propagation. Derivation of indirect and direct boundary integral equations. Introduction to other Green’s function based methods of analysis. Computational experiments in primarily two dimensions. Prerequisite: MEGN502. 3 hours lecture; 3 semester hours Spring Semester, odd numbered years.

MEGN521. INTRODUCTION TO DISCRETE ELEMENT METHODS (DEMS). 3.0 Semester Hrs.
Equivalent with EGGN535,
(I) Review of particle/ rigid body dynamics, numerical DEM solution of equations of motion for a system of particles/ rigid bodies, linear and nonlinear contact and impact laws dynamics, applications of DEM in mechanical engineering, materials processing and geo-mechanics. Prerequisites: CEEN311, MEGN315 and some scientific programming experience in C/C++ or Fortran. 3 hours lecture; 3 semester hours Spring semester of even numbered years.
MEGN530. BIOMEDICAL INSTRUMENTATION. 3.0 Semester Hrs.
Equivalent with BELS530, EGGN530.
The acquisition, processing, and interpretation of biological signals presents many unique challenges to the Biomedical Engineer. This course is intended to provide students with the knowledge to understand, appreciate, and address these challenges. At the end of the semester, students should have a working knowledge of the special considerations necessary to gathering and analyzing biological signal data. Prerequisites: EGGN250 MEL I, EENG281 Introduction to Electrical Circuits, Electronics, and Power, MEGN330 Introduction to Biomedical Engineering. 3 hours lecture; 3 semester hours. Fall odd years.

MEGN531. PROSTHETIC AND IMPLANT ENGINEERING. 3.0 Semester Hrs.
Equivalent with BELS527, EGGN527.
Prosthetics and implants for the musculoskeletal and other systems of the human body are becoming increasingly sophisticated. From simple joint replacements to myoelectric limb replacements and functional electrical stimulation, the engineering opportunities continue to expand. This course builds on musculoskeletal biomechanics and other BELS courses to provide engineering students with an introduction to prosthetics and implants for the musculoskeletal system. At the end of the semester, students should have a working knowledge of the challenges and special considerations necessary to apply engineering principles to augmentation or replacement in the musculoskeletal system. Prerequisites: Musculoskeletal Biomechanics [MEGN430], 3 hours lecture; 3 semester hours. Fall even years.

MEGN532. EXPERIMENTAL METHODS IN BIOMECHANICS. 3.0 Semester Hrs.
(I) 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, and applications. Strong emphasis on hands-on data collection and technical presentation of results. The course will culminate in individual projects combining multiple experimental measurement techniques. Prerequisite: Graduate Student Standing. 3 hours lecture; 3 semester hours.

MEGN535. MODELING AND SIMULATION OF HUMAN MOVEMENT. 3.0 Semester Hrs.
Equivalent with BELS526, EGGN526.
(II) Introduction to modeling and simulation in biomechanics. The course includes a synthesis of musculoskeletal properties and interactions with the environment to construct detailed computer models and simulations. The course will culminate in individual class projects related to each student's individual interests. Prerequisites: MEGN315 and MEGN330. 3 hours lecture; 3 semester hours.

MEGN536. COMPUTATIONAL BIOMECHANICS. 3.0 Semester Hrs.
Equivalent with BELS528, EGGN528.
Computational Biomechanics provides and introduction to the application of computer simulation to solve some fundamental problems in biomechanics and bioengineering. Musculoskeletal mechanics, medical image reconstruction, hard and soft tissue modeling, joint mechanics, and inter-subject variability will be considered. An emphasis will be placed on understanding the limitations of the computer model as a predictive tool and the need for rigorous verification and validation of computational techniques. Clinical application of biomechanical modeling tools is highlighted and impact on patient quality of life is demonstrated. Prerequisite: MEGN424, MEGN330. 3 hours lecture; 3 semester hours. Fall odd years.

MEGN537. PROBABILISTIC BIOMECHANICS. 3.0 Semester Hrs.
Equivalent with EGGN529, (II) MEGN537. PROBABILISTIC BIOMECHANICS The course introduces the application of probabilistic analysis methods in biomechanical systems. All real engineering systems, and especially human systems, contain inherent uncertainty due to normal variations in dimensional parameters, material properties, motion profiles, and loading conditions. The purpose of this course is to examine methods for including these sources of variation in biomechanical computations. Concepts of basic probability will be reviewed and applied in the context of engineering reliability analysis. Probabilistic analysis methods will be introduced and examples specifically pertaining to musculoskeletal biomechanics will be studied. Prerequisites: MEGN436/BELS428 or MEGN536/BELS528. 3 hours lecture, 3 semester hours. Spring even years.

MEGN540. MECHATRONICS. 3.0 Semester Hrs.
Equivalent with EGGN521.
(II) 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. Prerequisite: Graduate Student Standing. 3 hours lecture; 3 semester hours.

MEGN544. ROBOT MECHANICS: KINEMATICS, DYNAMICS, AND CONTROL. 3.0 Semester Hrs.
Equivalent with EGGN518.
(I) 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. Prerequisite: EENG307 and MEGN441. 3 hours lecture; 3 semester hours.

MEGN545. ADVANCED ROBOT CONTROL. 3.0 Semester Hrs.
Equivalent with EGGN514.
The focus is on mobile robotic vehicles. Topics covered are: navigation, mining applications, sensors, including vision, problems of sensing variations in rock properties, problems of representing human knowledge in control systems, machine condition diagnostics, kinematics, and path planning real time obstacle avoidance. Prerequisite: EENG307. 3 hours lecture; 3 semester hours. Spring semester of odd years.

MEGN551. ADVANCED FLUID MECHANICS. 3.0 Semester Hrs.
(I) This first year graduate course covers the fundamentals of incompressible fluid mechanics with a focus on differential analysis and building a strong foundation in the prerequisite concepts required for subsequent study of computational fluid dynamics and turbulence. The course is roughly divided into four parts covering (i) the governing equations of fluid mechanics, (ii) Stokes flows and ideal-fluid flows, (iii) boundary layer flows, and (iv) hydrodynamic stability and transition to turbulence. Prerequisites: MEGN351. 3 hours lecture; 3 semester hours.

MEGN552. VISCOUS FLOW AND BOUNDARY LAYERS. 3.0 Semester Hrs.
Equivalent with EGGN552.
(I) 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. Prerequisite: MEGN451, or CBEN430. 3 hours lecture; 3 semester hours.
MEGN553. INTRODUCTION TO COMPUTATIONAL TECHNIQUES FOR FLUID DYNAMICS AND TRANSPORT PHENOMENA. 3.0 Semester Hrs.
Equivalent with EGGN573.
(I) 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. 3 hours lecture; 3 semester hours.

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 (MEGN361) 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 heat and power, refrigeration and geothermal systems, fuel cells, turbomachinery, and heat transfer equipment are a focus. 3 lecture hours; 3 credit hours.

MEGN561. ADVANCED ENGINEERING THERMODYNAMICS. 3.0 Semester Hrs.
(I) 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. Prerequisites: MEGN351, MEGN361, and MEGN471. 3 hours lecture; 3 semester hours.

MEGN566. COMBUSTION. 3.0 Semester Hrs.
Equivalent with EGGN566.
(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. HVAC AND BUILDING ENERGY SYSTEMS. 3.0 Semester Hrs.
(I) 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. Prerequisites: MEGN351, MEGN361, MEGN471. 3 hours lecture; 3 semester hours.

MEGN569. FUEL CELL SCIENCE AND TECHNOLOGY. 3.0 Semester Hrs.
Equivalent with CBEN569,CHEN569,EGGN569,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.

MEGN570. ELECTROCHEMICAL SYSTEMS ENGINEERING. 3.0 Semester Hrs.
(I) 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 we 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. 3 hours lecture; 3 semester hours.

MEGN571. ADVANCED HEAT TRANSFER. 3.0 Semester Hrs.
Equivalent with EGGN571.
(II) An advanced course in heat transfer that supplements topics covered in MEGN471. Derivation and solution of governing heat transfer equations from conservation laws. Development of analytical and numerical models for conduction, convection, and radiation heat transfer, including transient, multidimensional, and multimode problems. Introduction to turbulence, boiling and condensation, and radiative transfer in participating media. 3 lecture hours; 3 credit hours.
MEGN583. ADDITIVE MANUFACTURING. 3.0 Semester Hrs.
(I) Additive Manufacturing (AM), also known as 3D Printing in the popular press, is an emerging manufacturing technology that will see widespread adoption across a wide range of industries during your career. Subtractive Manufacturing (SM) technologies (CNCs, drill presses, lathes, etc.) have been an industry mainstay for over 100 years. The transition from SM to AM technologies, the blending of SM and AM technologies, and other developments in the manufacturing world has direct impact on how we design and manufacture products. This course will prepare students for the new design and manufacturing environment that AM is unlocking. The graduate section of this course differs from the undergraduate section in that graduate students perform AM-related research. While students complete quizzes and homework, they do not take a midterm or final exam. Prerequisites: MEGN200 and MEGN201 or equivalent project classes. 3 hours lecture; 3 semester hours.

MEGN585. 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. Offered every other year. 3 hours lecture; 3 semester hours.

MEGN586. 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.

MEGN587. NONLINEAR OPTIMIZATION. 3.0 Semester Hrs.
Equivalent with MEGN487,
(II) We address 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. Prerequisite: MATH111. 3 hours lecture; 3 semester hours.

MEGN588. INTEGER OPTIMIZATION. 3.0 Semester Hrs.
Equivalent with MEGN488,
(I) We address the formulation of integer programming models, the brand-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. Prerequisite: none. 3 hours lecture; 3 semester hours. Years to be Offered: Every Other Year.

MEGN591. ADVANCED ENGINEERING DESIGN METHODS. 3.0 Semester Hrs.
Equivalent with EGGN503,
(I) Introduction to contemporary and advanced methods used in engineering design. Includes, need and problem identification, methods to understand the customer, the market and the competition. Techniques to decompose design problems to identify functions. Ideation methods to produce form from function. Design for X topics. Methods for prototyping, modeling, testing and evaluation of designs. Embodiment and detailed design processes. Prerequisites: EGGN491 and EGGN492, equivalent senior design project experience or industrial design experience, graduate standing. 3 hours lecture; 3 semester hours. Taught on demand.

MEGN592. RISK AND RELIABILITY ENGINEERING ANALYSIS AND DESIGN. 3.0 Semester Hrs.
(I) 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 information will be discussed. 3 hours lecture, 3 semester hours.

MEGN593. ENGINEERING DESIGN OPTIMIZATION. 3.0 Semester Hrs.
Equivalent with EGGN593,
The application of gradient, stochastic and heuristic optimization algorithms to linear and nonlinear optimization problems in constrained and unconstrained design spaces. Students will consider problems in constrained and unconstrained design spaces. Students will consider problems with continuous, integer and mixed-integer variables, problems with single or multiple objectives and the task modeling design spaces and constraints. Design optimization methods are becoming of increasing importance in engineering design and offer the potential to reduce design cycle times while improving design quality by leveraging simulation and historical design data. Prerequisites: Experience with computer programming languages, graduate or senior standing. 3 hours lecture; 3 semester hours.

MEGN598. SPECIAL TOPICS IN MECHANICAL ENGINEERING. 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: none. Variable credit: 0 to 6 credit hours. Repeatable for credit under different titles.
MEGN599. 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.

MEGN686. 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.

MEGN688. 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 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. Offered every other year. Prerequisite: MEGN588. 3 hours lecture; 3 semester hours. Years to be Offered: Every Other Year.

MEGN698. SPECIAL TOPICS. 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: 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.
Equivalent with EGGN707M, (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.

DTCN501. INTRODUCTION TO DATA CENTER ENGINEERING. 3.0 Semester Hrs.
(I, II) This unique course will develop students' foundational knowledge in critical disciplines related to large-scale data center infrastructure design and performance. The course is intended for students with a B.S. in engineering, computer science, or applied and engineering physics who are interested in careers and/or opportunities in data center engineering and management. The course will incorporate real data center examples for introducing analysis of data center design and computing hardware and network requirements; engineering principles for data center power system design, distribution, and control; heat transfer systems for computer system thermal management and building HVAC; and large-scale data file organization, information system architecture, and network and software security. The course will conclude with lectures and an assignment related to sustainability and robustness for data center engineering and design. 3 hours lecture; 3 semester hours.

DTCN502. DATA CENTER INFRASTRUCTURE MANAGEMENT. 3.0 Semester Hrs.
(I, II) This course conveys the basic principles for operating, managing, and optimizing the hardware and software necessary for a large, modern data center. Students will learn how data center components are integrated and managed through software for various applications and in general for security, efficiency, adaptability, robustness, and sustainability. It is intended for graduate students with backgrounds in engineering or computer science. The students will become familiar with best practices in the industry and will demonstrate their knowledge by developing a operations management plan for a specific data center application. 3 hours lecture; 3 semester hours.

DTCN503. DATA CENTER ENGINEERING GRADUATE SEMINAR. 1.0 Semester Hr.
(I, II) The Data Center Engineering Seminar will provide students a broad knowledge of current industry and research developments in analysis, design, and operations of Data Center Engineering through once a week discussions and/or seminars from invited guest speakers presenting topics related to data center design, operations, and economics. Students will prepare several short reports on industry developments and/or academic research related to presentations and will deliver a technical presentation and lead a subsequent discussion on an approved topic relevant for the industry. Corequisite: DTCN501. 1 hour seminar; 1 semester hour.

DTCN591. DATA CENTER ENGINEERING DESIGN AND ANALYSIS. 2.0 Semester Hrs.
(I, II) In this graduate-level course, students will participate in a directed team-based project learning through planning, designing, and analyzing a large, modern data center for an industry- or government-relevant application. The course will build on content learned in pre-requisite courses on an Introduction to Data Center Engineering and on Data Center Infrastructure Management. Students will collaborate in multi-disciplinary teams to develop and present the design and analysis of a large, modern data center design for an industry or government application. 2 hours seminar; 2 semester hours.

FEGN525. ADVANCED FEA THEORY & PRACTICE. 3.0 Semester Hrs.
(I) 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, variational methods, and weighted residual methods. Common 1D, 2D, and 3D element formulations are discussed and key limitations examined. The commercial FEA software Abaqus is used for hands-on experience. Online course. 3 hours lecture; 3 semester hours.
FEGN526. STATIC AND DYNAMIC APPLICATIONS IN FEA. 3.0 Semester Hrs.
(I) 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. 3 hours lecture; 3 semester hours.

FEGN527. NONLINEAR APPLICATIONS IN FEA. 3.0 Semester Hrs.
(II) 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. 3 hours lecture; 3 semester hours.

FEGN528. FEA FOR ADVANCED DESIGN APPLICATIONS. 3.0 Semester Hrs.
(II) 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. 3 hours lecture; 3 semester hours.

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