

# Mechanical Engineering

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## 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, and 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 and Energy Systems, (3) Solid Mechanics, Materials, and Manufacturing, and (4) Robotics and Automation. 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 in this area addresses rehabilitation engineering, computer-assisted surgery and medical robotics, patient-specific biomechanical modeling, intelligent prosthetics and implants, and bioinstrumentation.

**Robotics and Automation** applies 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, magnetic guidance for placement of probes for deep brain stimulation and remote telesurgery. We use both high-performance computational and physical prototyping methods to advance research in these areas.

**Solid Mechanics, Materials, and Manufacturing** develops novel computational and experimental solutions for problems in the mechanical behavior of advanced materials and processes. Research in the division spans length scales 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 microscale to the meso- and macroscale. Much of the research is computational in nature, using advanced methods such as molecular dynamics and 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 & Energy Systems** addresses a wide array of cutting-edge topics that rely on thermodynamics, heat transport, fluid mechanics, and chemical and phase change phenomena in engineered systems. Students, faculty, and research staff implement advanced experimental diagnostics and numerical simulation tools to solve problems related to energy storage, conversion and utilization; environmental impacts and safety; sustainable transportation and fuels; water purification and processing; and thermochemical and material process applications. Research projects involve collaborations with partners in other disciplines, national labs, and sponsoring companies, and projects range in scope from experimental characterization and modeling of processes on the molecular scale to testing and technoeconomic of commercial-scale energy 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' 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.

## 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 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 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 coursework.

## 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. *All MS students must complete nine credits of course work within 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

MEGN502	ADVANCED ENGINEERING ANALYSIS	3.0
MEGN503	GRADUATE SEMINAR Enrollment required every fall and spring semester	0.0
RESEARCH CORE	Courses from one Research Division List	9.0
TECHNICAL ELECTIVES	Technical Electives <sup>500-level or above courses approved by Advisor/Thesis Committee.</sup>	9.0
ME ELECTIVES	Any 500-level or above MEGN, AMFG, or FEGN course	3.0
MEGN707	GRADUATE THESIS / DISSERTATION RESEARCH CREDIT	6.0
<b>Total Semester Hrs</b>		<b>30.0</b>

*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.

## MS Non-Thesis Degree

MEGN502	ADVANCED ENGINEERING ANALYSIS	3.0
RESEARCH CORE	Course from one Research Division List	9.0
TECHNICAL ELECTIVES	Technical Electives <sup>500-level or above courses approved by Advisor.</sup>	9.0
ME ELECTIVES	Any 500-level or above MEGN, AMFG, or FEGN course	9.0
<b>Total Semester Hrs</b>		<b>30.0</b>

*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.

Online Modality available for Masters Non-Thesis.

## Doctor of Philosophy Degree Requirements

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

MEGN502	ADVANCED ENGINEERING ANALYSIS	3.0
MEGN503	GRADUATE SEMINAR Enrollment required every fall and spring semester	0.0
RESEARCH CORE	Courses from one Research Division List	9.0
TECHNICAL ELECTIVES	Technical Electives <sup>Courses must be 500-level or above and must be approved by the Advisor/Thesis Committee.</sup>	24.0
MEGN707	GRADUATE THESIS / DISSERTATION RESEARCH CREDIT	30.0
TOTAL CREDITS	Remaining credits can come from Research and/or Technical Electives	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 ME faculty has adopted

a PhD timeline that outlines milestones students should reach on a semester-by-semester basis. Each milestone is listed here with more detailed explanations given below:

MILESTONE	TIMELINE
Select a permanent advisor	Second semester
Complete the PhD qualifying examination	Third semester
Establish a dissertation committee and present research proposal	Fourth semester
Complete all core curriculum course requirements	Fourth semester
Submit Degree Audit and Admission to Candidacy forms	Fourth 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 3.3 are eligible to take the qualifying exam. Students must have completed at least four 500-level MEGN courses before taking the qualifier. These courses must include three core 500-level courses (MEGN 502 counts toward this core requirement).

The PhD qualifying exam will be administered at a specific date during every semester. The Department Qualifying Exam Chair oversees the process and ensures that the exam is administered fairly. Students must take the exam by the end of their third semester in the Mechanical Engineering PhD program.

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.

Students, in consultation with faculty advisors, will choose three topical areas. The oral qualifying exam will be conducted by the qualifying exam

committee (three Mechanical Engineering faculty) and the student's advisor. Students will receive a journal paper for each topical area at least one week before the exam. Oral exam questions will be based upon the three selected journal papers.

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.

A written Research Proposal document consisting of no more than 10 pages will be provided to the Committee in advance of the presentation with the expectation of achieving 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, 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 30-45 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. For most students, Research Proposal presentation will happen the semester after successfully passing the qualifier. The research proposal must be completed before admission to candidacy. If the qualifier is passed after the fourth semester, admission to candidacy may be granted prior to the research proposal with ME Graduate Curriculum Committee approval.

*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 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 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 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. 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 research division's MEGN 503 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 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. 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.

*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

AMFG501	ADDITIVE MANUFACTURING
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, MATERIALS, AND MANUFACTURING

AMFG501	ADDITIVE MANUFACTURING
FEGN525	ADVANCED FEA THEORY & PRACTICE
MEGN510	THEORY OF ELASTICITY
MEGN511	FATIGUE AND FRACTURE
MEGN514	CONTINUUM MECHANICS
MEGN515	COMPUTATIONAL MECHANICS
MEGN517	INELASTIC CONSTITUTIVE RELATIONS

### THERMAL FLUID ENERGY SYSTEMS

MEGN551	ADVANCED FLUID MECHANICS
MEGN552	VISCOUS FLOW AND BOUNDARY LAYERS
MEGN553	INTRODUCTION TO COMPUTATIONAL TECHNIQUES FOR FLUID DYNAMICS AND TRANSPORT PHENOMENA
MEGN560	DESIGN AND SIMULATION OF THERMAL SYSTEMS
MEGN561	ADVANCED ENGINEERING THERMODYNAMICS
MEGN566	COMBUSTION
MEGN571	ADVANCED HEAT TRANSFER

## 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: EGGN250, EENG281 or equivalent, and MATH201 or equivalent, Graduate student status.

### MEGN502. ADVANCED ENGINEERING ANALYSIS. 3.0 Semester Hrs.

(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.

(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-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.

Prerequisite: Graduate standing. 1 hour per week; 0 semester hours. Course is repeatable, but no coursework credit is awarded.

### MEGN510. 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 MLGN517.

### MEGN511. FATIGUE AND FRACTURE. 3.0 Semester Hrs.

Equivalent with MTGN545,

(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 semesters, odd numbered years.

### MEGN512. ADVANCED ENGINEERING VIBRATION. 3.0 Semester Hrs.

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 MLGN511,

Linear irreversible thermodynamics, force-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), 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, Indicical 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 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. 3 lecture hours, 3 semester hours. Prerequisite: MEGN502.

**MEGN517. INELASTIC CONSTITUTIVE RELATIONS. 3.0 Semester Hrs.**

(II) This is a graduate course on inelastic constitutive relations of solid materials. The goal of the course is to provide students working in solid mechanics and metallurgy with a foundation in theory and models of inelastic material behaviors. The behaviors we cover include plasticity, thermoelasticity, nonlinear elasticity, and phase transformations. We dive in at several length scales - 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.**

(II) 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.**

(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.

**MEGN531. PROSTHETIC AND IMPLANT ENGINEERING. 3.0 Semester Hrs.**

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. Prerequisite: MEGN430.

**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; 3.0 semester hours.

**MEGN535. MODELING AND SIMULATION OF HUMAN MOVEMENT. 3.0 Semester Hrs.**

Introduction to modeling and simulation in biomechanics. The course includes a synthesis of musculoskeletal properties, interactions with the environment, and computational optimization to construct detailed computer models and simulations of human movement. Prerequisite: MEGN315 and MEGN330.

**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 of a semester-long project to develop and evaluate an artificial knee implant. Leading commercial software tools are introduced with hands-on exercises. An emphasis is placed on understanding the limitations of the computer model as a predictive tool 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.

**MEGN537. PROBABILISTIC BIOMECHANICS. 3.0 Semester Hrs.**

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. Prerequisite: MEGN436 or MEGN536.

**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.

**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. 3 hours lecture; 3 semester hours. Prerequisite: EENG307 and MEGN441.

**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. Prerequisite: EENG307.

**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. 3 hours lecture; 3 semester hours.

**MEGN552. VISCOUS FLOW AND BOUNDARY LAYERS. 3.0 Semester Hrs.**

(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.**

(II) 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.**

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. 3 hours lecture; 3 semester hours. Prerequisite: MEGN351, MEGN361, and MEGN471.

**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. 3 hours lecture; 3 semester hours. Prerequisite: MEGN351, MEGN361, MEGN471.

**MEGN569. FUEL CELL SCIENCE AND TECHNOLOGY. 3.0 Semester Hrs.**

Equivalent with CBEN569, CHEN569, 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 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.**

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.

**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.

**MEGN583. ADDITIVE MANUFACTURING. 3.0 Semester Hrs.**

(II) 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.

**MEGN584. MODELING MATERIALS PROCESSING. 3.0 Semester Hrs.**

This course aims to enable students to examine a given materials processing operation or manufacturing problem, identify the important phenomena, develop simple quantitative models of those phenomena, and apply them to obtain reasonable solutions to practical design issues and problems. Phenomena involving fluid flow, heat transfer, solidification, diffusion, and thermal-mechanical behavior are related to terms in governing equations based on heat, mass, and momentum balances. These equations are simplified by formal estimation and scaling to create mechanistic process models, often selected from classic analytical solutions. Example applications to manufacturing processes for metals and polymers include controlled cooling, extrusion, casting, and welding. Prerequisite: Undergraduate degree in Mechanical Engineering or equivalent (that includes relevant courses of calculus, differential equations, materials and/or manufacturing, heat transfer, fluid mechanics, and solid mechanics) or instructor consent.

**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. 3 hours lecture; 3 semester hours.

**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. Offered every other year.

**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.

**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.

**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 information will be discussed.

**MEGN597. CASE STUDY - MATERIALS SCIENCE. 0.5-6 Semester Hr.**

Individual research or special problem projects supervised by a faculty member.

**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.

**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-difference methods, 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 homeworks, through which students will learn to how 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.

**MEGN671. RADIATION HEAT TRANSFER. 3.0 Semester Hrs.**

Accurate radiative transfer models are essential in many fields, including: combustion, propulsion, astronomy, solar technology, and climate science, to name only a few. The complex nature of radiative transfer can be intimidating, and calculations can be computationally expensive. In the first half of this course, we will study the role of material and surface properties on radiative transfer and develop and solve models for radiation exchange between surfaces (applicable to solar technology and high temperature systems). In the second half of the course, we will tackle radiation propagation through absorbing, scattering, and emitting media (gases, aerosols, semitransparent materials). We will model these systems using the Radiative Transfer Equation (RTE) and explore a few approaches to solving the RTE for select environments. Prerequisite: MEGN471.

**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 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. 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.**

(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 an 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.**

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.

**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.

**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.

**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.

**Professor and Department Head**

Carl Frick

**Emeriti Professors**

Joan Gosink

Robert King

Graham G.W. Mustoe

Terry E. Parker

## **Emeriti Associate Professors**

Dave Munoz

John P.H. Steele

## **Professors**

Mohsen Asle Zaeem

John R. Berger

Robert Braun, Rowlinson Professor of Mechanical Engineering

Cristian V. Ciobanu

Gregory S. Jackson

Robert J. Kee, George R. Brown Distinguished Professor

Alexandra Newman

Brian G. Thomas

## **Associate Professors**

Steven DeCaluwe

Mark Deinert

Veronica Eliasson

Joy Gockel

Owen Hildreth

Leslie Lamberson

Anthony J. Petrella

Andrew Petruska

Jason Porter

Anne Silverman, Rowlinson Associate Professor of Mechanical Engineering

Neal Sullivan

Paulo Tabares-Velasco

Nils Tilton

Garritt Tucker, Director of Graduate Studies - ME

Ruichong "Ray" Zhang

Xiaoli Zhang

## **Assistant Professor**

Andrew Osborne

## **Professors of Practice**

Angel Abbud-Madrid

Craig Brice

Christopher Dreyer

George Sowers

## **Teaching Professors**

Kristine Csavina, Assistant Department Head and Director of Undergraduate Studies - ME

Ventzi Karaivanov

## **Teaching Associate Professors**

Jeff Ackerman

Joel M. Bach

Daniel Blood

Oyvind Nilsen

Derrick Rodriguez

Jeff Wheeler

## **Teaching Assistant Professors**

Brian Donovan

Adam Duran

Stephen Geer

Gary Nave

Kelly Rickey

Polina Ringler

Jim Wong

## **Affiliate Professor of Mechanical Engineering**

Michael Mooney

## **Research Associate Professors**

Sandrine Ricote

Huayang Zhu

## **Research Assistant Professors**

Ankit Gupta

Carolina Herradon Hernandez

Garrison Hommer

Xingchao Wang