Chemical and Biological Engineering

Degrees Offered
- Master of Science (Chemical Engineering)
- Doctor of Philosophy (Chemical Engineering)

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

Program Requirements
See required curriculum below.

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

The essential undergraduate courses include:

<table>
<thead>
<tr>
<th>Course</th>
<th>Title</th>
<th>Credit</th>
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<tbody>
<tr>
<td>CBEN201</td>
<td>MATERIAL AND ENERGY BALANCES</td>
<td>3.0</td>
</tr>
<tr>
<td>CBEN307</td>
<td>FLUID MECHANICS</td>
<td>3.0</td>
</tr>
<tr>
<td>CBEN308</td>
<td>HEAT TRANSFER</td>
<td>3.0</td>
</tr>
<tr>
<td>CBEN357</td>
<td>CHEMICAL ENGINEERING THERMODYNAMICS</td>
<td>3.0</td>
</tr>
<tr>
<td>CBEN375</td>
<td>CHEMICAL ENGINEERING SEPARATIONS</td>
<td>3.0</td>
</tr>
<tr>
<td>CBEN418</td>
<td>KINETICS AND REACTION ENGINEERING</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Total Semester Hrs: 18.0

Required Curriculum

Master of Science Program

Master of Science (with Thesis)
Students entering the Master of Science (with thesis) program with an acceptable undergraduate degree in chemical engineering are required to take a minimum of 18 semester hours of coursework. All students must complete:

Chemical Engineering core graduate courses

<table>
<thead>
<tr>
<th>Course</th>
<th>Title</th>
<th>Credit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBEN507</td>
<td>APPLIED MATHEMATICS IN CHEMICAL ENGINEERING</td>
<td>3.0</td>
</tr>
<tr>
<td>CBEN509</td>
<td>ADVANCED CHEMICAL ENGINEERING THERMODYNAMICS</td>
<td>3.0</td>
</tr>
<tr>
<td>CBEN516</td>
<td>TRANSPORT PHENOMENA</td>
<td>3.0</td>
</tr>
<tr>
<td>CBEN518</td>
<td>REACTION KINETICS AND CATALYSIS</td>
<td>3.0</td>
</tr>
<tr>
<td>ELECT</td>
<td>Approved Coursework Electives</td>
<td>6.0</td>
</tr>
<tr>
<td>RESEARCH</td>
<td>Research Credits or Coursework</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Total Semester Hrs: 30.0

Students must take a minimum of 6 research credits, complete, and defend an acceptable Masters dissertation. Upon approval of the thesis committee, graduate credit may be earned for 400-level courses. Between coursework and research credits a student must earn a minimum of 30 total semester hours. Full-time Masters students must enroll in graduate colloquium (CBEN605) each semester.

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

Chemical Engineering core graduate courses

<table>
<thead>
<tr>
<th>Course</th>
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<th>Credit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBEN507</td>
<td>APPLIED MATHEMATICS IN CHEMICAL ENGINEERING</td>
<td>3.0</td>
</tr>
<tr>
<td>CBEN509</td>
<td>ADVANCED CHEMICAL ENGINEERING THERMODYNAMICS</td>
<td>3.0</td>
</tr>
<tr>
<td>CBEN516</td>
<td>TRANSPORT PHENOMENA</td>
<td>3.0</td>
</tr>
<tr>
<td>CBEN518</td>
<td>REACTION KINETICS AND CATALYSIS</td>
<td>3.0</td>
</tr>
<tr>
<td>ELECT</td>
<td>Approved Electives</td>
<td>18.0</td>
</tr>
</tbody>
</table>

Total Semester Hrs: 30.0

Students may complete an acceptable engineering report for up to 6 hours of academic credit. Upon approval of the thesis committee, graduate credit may be earned for selected 400-level courses. Full-time Masters students must enroll in graduate colloquium (CBEN605) each semester.

CSM undergraduates enrolled in the combined BS/MS degree program must meet the requirements described above for the MS portion of their degree (both thesis and non-thesis). Students accepted into the combined program may take graduate coursework and/or research credits as an undergraduate and have them applied to their MS degree.

Doctor of Philosophy Program
The course of study for the PhD degree consists of a minimum of 30 semester hours of coursework. All PhD students must complete:

Core courses

<table>
<thead>
<tr>
<th>Course</th>
<th>Title</th>
<th>Credit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBEN507</td>
<td>APPLIED MATHEMATICS IN CHEMICAL ENGINEERING</td>
<td>3.0</td>
</tr>
<tr>
<td>CBEN509</td>
<td>ADVANCED CHEMICAL ENGINEERING THERMODYNAMICS</td>
<td>3.0</td>
</tr>
<tr>
<td>CBEN516</td>
<td>TRANSPORT PHENOMENA</td>
<td>3.0</td>
</tr>
<tr>
<td>CBEN518</td>
<td>REACTION KINETICS AND CATALYSIS</td>
<td>3.0</td>
</tr>
<tr>
<td>CBEN568</td>
<td>INTRODUCTION TO CHEMICAL ENGINEERING</td>
<td>3.0</td>
</tr>
<tr>
<td>CBEN6XX</td>
<td>600-Level Coursework Electives</td>
<td>6.0</td>
</tr>
<tr>
<td>CBEN707</td>
<td>Graduate Research Credit</td>
<td>42.0</td>
</tr>
</tbody>
</table>

(up to 12 hours per semester)
In addition, students must complete and defend an acceptable Doctoral dissertation. Upon approval of the thesis committee, graduate credit may be earned for 400-level courses. Full-time PhD students must enroll in graduate colloquium (CBEN605) each semester.

Students in the PhD program are required to pass both a Qualifying Exam and the PhD Proposal Defense. After successful completion of 30 semester hours of coursework and completion of the PhD proposal defense, PhD candidates will be awarded a non-thesis Master of Science Degree. The additional requirements for the PhD program are described below.

**PhD Qualifying Examination**

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

The qualifying examination will cover the traditional areas of Chemical Engineering, and will consist of two parts: GPA from core graduate classes (CBEN507, CBEN509, CBEN516, and CBEN518) and an oral examination. The oral examination will consist of a presentation by the student on a technical paper from chemical engineering literature. Students will choose a paper from a list determined by the faculty. Papers for the oral examination will be distributed well in advance of the oral portion of the exam so students have sufficient time to prepare their presentations. The student is required to relate the paper to the core chemical engineering classes and present a research plan, followed by questions from the faculty. A 1-2 page paper on the research plan is due the Friday prior to the oral examination.

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

**PhD Proposal Defense**

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

Two negative votes from the doctoral committee members are required for failure of the PhD Proposal Defense. In the case of failure, one re-examination will be allowed upon petition to the Department Head. Failure to complete the PhD Proposal Defense within the allotted time without an approved postponement will result in failure. Under extenuating circumstances a student may postpone the exam with approval of the Graduate Affairs committee, based on the recommendation of the student’s thesis committee. In such cases, a student must submit a written request for postponement that describes the circumstances and proposes a new date. Requests for postponement must be presented to the thesis committee no later than 2 weeks before the end of the semester in which the exam would normally have been taken.
Courses
CBEN504. ADVANCED PROCESS ENGINEERING ECONOMICS. 3.0 Semester Hrs.
Equivalent with CHEN504, Advanced engineering economic principles applied to original and alternate investments. Analysis of chemical and petroleum processes relative to marketing and return on investments. Prerequisite: none. 3 hours lecture; 3 semester hours.

CBEN505. NUMERICAL METHODS IN CHEMICAL ENGINEERING. 3.0 Semester Hrs.
Equivalent with CHEN505, Engineering applications of numerical methods. Numerical integration, solution of algebraic equations, matrix 54 Colorado School of Mines Graduate Bulletin 2011 2012 algebra, ordinary differential equations, and special emphasis on partial differential equations. Emphasis on application of numerical methods to chemical engineering problems which cannot be solved by analytical methods. Prerequisite: none. 3 hours lecture; 3 semester hours.

CBEN506. ADVANCED CHEMICAL ENGINEERING THERMODYNAMICS. 3.0 Semester Hrs.
Equivalent with CHEN506, Extension and amplification of under graduate chemical engineering thermodynamics. Topics will include the laws of thermodynamics, thermodynamic properties of pure fluids and fluid mixtures, phase equilibria, and chemical reaction equilibria. Prerequisite: CBEN357 or equivalent. 3 hours lecture; 3 semester hours.

CBEN507. APPLIED MATHEMATICS IN CHEMICAL ENGINEERING. 3.0 Semester Hrs.
Equivalent with CHEN507, (I, II) This course stresses the application of mathematics to problems drawn from chemical and biological engineering fundamentals such as thermodynamics, transport phenomena, and kinetics. Formulation and solution of ordinary and partial differential equations arising in chemical engineering or related processes or operations are discussed. Prerequisite: Undergraduate differential equations course; undergraduate chemical engineering courses covering reaction kinetics, and heat, mass and momentum transfer. 3 hours lecture; 3 semester hours.

CBEN513. SELECTED TOPICS IN CHEMICAL ENGINEERING. 1-3 Semester Hr.
Equivalent with CHEN513, Selected topics chosen from special interests of instructor and students. Course may be repeated for credit on different topics. Prerequisite: none. 1 to 3 semester hours lecture/discussion; 1 to 3 semester hours.

CBEN516. TRANSPORT PHENOMENA. 3.0 Semester Hrs.
Equivalent with CHEN516, (I) Principles of momentum, heat, and mass transport with applications to chemical and biological processes. Analytical methods for solving ordinary and partial differential equations in chemical engineering with an emphasis on scaling and approximation techniques. Convective transport in the context of boundary layer theory and development of heat and mass transfer coefficients. Introduction to computational methods for solving coupled transport problems in irregular geometries. 3 hours lecture; 3 semester hours.

CBEN518. REACTION KINETICS AND CATALYSIS. 3.0 Semester Hrs.
Equivalent with CHEN518, (I) This course applies the fundamentals of kinetics, transport and thermodynamics to the analysis of gas-phase and catalytic reactions. A focus is placed on a molecular description of chemical kinetics with applications to the design and analysis chemical and biological reactors, complex reaction networks, and catalysis. Prerequisite: CBEN418 or equivalent. 3 hours lecture; 3 semester hours.

CBEN524. COMPUTER-AIDED PROCESS SIMULATION. 3.0 Semester Hrs.
Equivalent with CHEN524, Advanced concepts in computer-aided process simulation are covered. Topics include optimization, heat exchanger networks, data regression analysis, and separations systems. Use of industry-standard process simulation software (Aspen Plus) is stressed. Prerequisite: none. 3 hours lecture; 3 semester hours.

CBEN531. IMMUNOLOGY FOR SCIENTISTS AND ENGINEERS. 3.0 Semester Hrs.
Equivalent with BELSS31, (II) This course introduces the basic concepts of immunology and their applications in engineering and science. We will discuss the molecular, biochemical and cellular aspects of the immune system including structure and function of the innate and acquired immune systems. Building on this, we will discuss the immune response to infectious agents and the material science of introduced implants and materials such as heart valves, artificial joints, organ transplants and lenses. We will also discuss the role of the immune system in cancer, allergies, immune deficiencies, vaccination and other applications such as immunoassay and flow cytometry. Prerequisites: Biology BIOL110 or equivalent or graduate standing.
CBEN535. INTERDISCIPLINARY MICROELECTRONICS PROCESSING LABORATORY. 3.0 Semester Hrs.
Equivalent with CHEN435, CHEN535, MLGN535, PHGN435, PHGN535, Application of science and engineering principles to the design, fabrication, and testing of microelectronic devices. Emphasis on specific unit operations and the interrelation among processing steps. 1 hour lecture, 4 hours lab; 3 semester hours.

CBEN550. MEMBRANE SEPARATION TECHNOLOGY. 3.0 Semester Hrs.
Equivalent with CHEN550, This course is an introduction to the fabrication, characterization, and application of synthetic membranes for gas and liquid separations. Industrial membrane processes such as reverse osmosis, filtration, pervaporation, and gas separations will be covered as well as new applications from the research literature. The course will include lecture, experimental, and computational (molecular simulation) laboratory components. Prerequisites: CBEN375, CBEN430. 3 hours lecture; 3 semester hours.

CBEN554. APPLIED BIOINFORMATICS. 3.0 Semester Hrs.
Equivalent with BELS554, (II) In this course we will discuss the concepts and tools of bioinformatics. The molecular biology of genomics and proteomics will be presented and the techniques for collecting, storing, retrieving and processing such data will be discussed. Topics include analyzing DNA, RNA and protein sequences, gene recognition, gene expression, protein structure prediction, modeling evolution, utilizing BLAST and other online tools for the exploration of genome, proteome and other available databases. In parallel, there will be an introduction to the PERL programming language. Practical applications to biological research and disease will be presented and students given opportunities to use the tools discussed. General Biology BIOL110 or Graduate standing.

CBEN555. POLYMER AND COMPLEX FLUIDS COLLOQUIUM. 1.0 Semester Hr.
Equivalent with BELS555, CHEN555, CHGN555, MLGN555, The Polymer and Complex Fluids Group at the Colorado School of Mines combines expertise in the areas of flow and field based transport, intelligent design and synthesis as well as nanomaterials and nanotechnology. A wide range of research tools employed by the group includes characterization using rheology, scattering, microscopy, microfluidics and separations, synthesis of novel macromolecules as well as theory and simulation involving molecular dynamics and Monte Carlo approaches. The course will provide a mechanism for collaboration between faculty and students in this research area by providing presentations on topics including the expertise of the group and unpublished, ongoing campus research. Prerequisites: none. 1 hour lecture; 1 semester hour. Repeatable for credit to a maximum of 3 hours.

CBEN568. INTRODUCTION TO CHEMICAL ENGINEERING RESEARCH AND TEACHING. 3.0 Semester Hrs.
Equivalent with CHEN568, (I) Students will be expected to apply chemical engineering principles to critically analyze theoretical and experimental research results in the chemical engineering literature, placing it in the context of the related literature, and interact effectively with students in classroom. Skills to be developed and discussed include oral presentations, technical writing, proposal writing, principles of hypothesis driven research, critical review of the literature, research ethics, research documentation (the laboratory notebook), research funding, types of research, pedagogical methods, and assessment tools. Prerequisites: graduate student in Chemical and Biological Engineering in good standing. 3 semester hours.

CBEN569. FUEL CELL SCIENCE AND TECHNOLOGY. 3.0 Semester Hrs.
Equivalent with CHEN569, EGGN569, MEGN569, MLGN569, MTGN569, (I) Investigate fundamentals of fuel-cell operation and electrochemistry from a chemical-thermodynamics and materials- science perspective. Review types of fuel cells, fuel-processing requirements and approaches, and fuel-cell system integration. Examine current topics in fuel-cell science and technology. Fabricate and test operational fuel cells in the Colorado Fuel Cell Center. 3 credit hours.

CBEN570. INTRODUCTION TO MICROFLUIDICS. 3.0 Semester Hrs.
Equivalent with CHEN570, This course introduces the basic principles and applications of microfluidics systems. Concepts related to microscale fluid mechanics, transport, physics, and biology are presented. To gain familiarity with small-scale systems, students are provided with the opportunity to design, fabricate, and test a simple microfluidic device. Students will critically analyze the literature in this emerging field. Prerequisites: CBEN307 or equivalent. 3 hours lecture, 3 semester hours.

CBEN580. NATURAL GAS HYDRATES. 3.0 Semester Hrs.
Equivalent with CHEN580, The purpose of this class is to learn about clathrate hydrates, using two of the instructor's books, (1) Clathrate Hydrates of Natural Gases, Third Edition (2008) co authored by C.A.Koh, and (2) Hydrate Engineering, (2000). Using a basis of these books, and accompanying programs, we have abundant resources to act as professionals who are always learning. 3 hours lecture; 3 semester hours.

CBEN584. FUNDAMENTALS OF CATALYSIS. 3.0 Semester Hrs.
Equivalent with CHEN584, The basic principles involved in the preparation, characterization, testing and theory of heterogeneous and homo geneous catalysts are discussed. Topics include chemisorption, adsorption isotherms, diffusion, surface kinetics, promoters, poisons, catalyst theory and design, acid base catalysis and soluble transition metal complexes. Examples of important industrial applications are given. Prerequisite: none. 3 hours lecture; 3 semester hours.

CBEN598. 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.

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

CBEN604. TOPICAL RESEARCH SEMINARS. 1.0 Semester Hr.
Equivalent with CHEN604, Lectures, reports, and discussions on current research in chemical engineering, usually related to the student’s thesis topic. Sections are operated independently and are directed toward different research topics. Course may be repeated for credit. Prerequisite: none. 1 hour lecture-discussion; 1 semester hour. Repeatable for credit to a maximum of 3 hours.
CBEN605. COLLOQUIUM. 1.0 Semester Hr.
Equivalent with CHEN605.
Students will attend a series of lectures by speakers from industry, academia, and government. Primary emphasis will be on current research in chemical engineering and related disciplines, with secondary emphasis on ethical, philosophical, and career-related issues of importance to the chemical engineering profession. Prerequisite: Graduate status. 1 hour lecture; 1 semester hour. Repeatable for credit to a maximum of 10 hours.

CBEN608. ADVANCED TOPICS IN FLUID MECHANICS. 1-3 Semester Hr.
Equivalent with CHEN608.
Indepth analysis of selected topics in fluid mechanics with special emphasis on chemical engineering applications. Prerequisite: CBEN508. 1 to 3 hours lecture discussion; 1 to 3 semester hours.

CBEN609. ADVANCED TOPICS IN THERMODYNAMICS. 1-3 Semester Hr.
Equivalent with CHEN609.
Advanced study of thermodynamic theory and application of thermodynamic principles. Possible topics include stability, critical phenomena, chemical thermodynamics, thermodynamics of polymer solutions and thermodynamics of aqueous and ionic solutions. Prerequisite: none. 1 to 3 semester hours.

CBEN610. APPLIED STATISTICAL THERMODYNAMICS. 3.0 Semester Hrs.
Equivalent with CHEN610.
Principles of relating behavior to microscopic properties. Topics include element of probability, ensemble theory, application to gases and solids, distribution theories of fluids, and transport properties. Prerequisite: none. 3 hours lecture; 3 semester hours.

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

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

CBEN624. APPLIED STATISTICAL MECHANICS. 4.0 Semester Hrs.
(II) This course will introduce the both rigorous and approximate theories to estimate the macroscopic thermodynamic properties of systems based on laws that control the behavior of molecules. Course contents include classical dynamics and phase space, different types of ensembles, ideal and interacting gases, modern theory of liquids, ideal solids, as well as molecular simulation techniques. Prerequisite: undergraduate-level classical thermodynamics. 4 hours lecture; 4 semester hours.

CBEN625. MOLECULAR SIMULATION. 3.0 Semester Hrs.
Equivalent with CHEN625.
Principles and practice of modern computer simulation techniques used to understand solids, liquids, and gases. Review of the statistical foundation of thermodynamics followed by in-depth discussion of Monte Carlo and Molecular Dynamics techniques. Discussion of intermolecular potentials, extended ensembles, and mathematical algorithms used in molecular simulations. Prerequisites: CBEN509 or equivalent, CBEN610 or equivalent recommended. 3 hours lecture; 3 semester hours.

CBEN690. SUPERVISED TEACHING OF CHEMICAL ENGINEERING. 2.0 Semester Hrs.
Equivalent with CHEN690.
Individual participation in teaching activities. Discussion, problem review and development, guidance of laboratory experiments, course development, supervised practice teaching. Course may be repeated for credit. Prerequisite: Graduate standing, appointment as a graduate student instructor. 6 to 10 hours supervised teaching; 2 semester hours.

CBEN698. SPECIAL TOPICS IN CHEMICAL 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.

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

CBEN707. GRADUATE THESIS / DISSERTATION RESEARCH CREDIT. 1-15 Semester Hr.
Equivalent with CHEN707.
(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.