King Abdullah University of Science and Technology

KAUST

GRADUATE PROGRAMS GUIDE

COURSE OFFERINGS + DEGREE REQUIREMENTS

2009

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1. KAUST GRADUATE PROGRAMS

KAUST offers several graduate programs leading to M.S. and Ph.D. degrees. These include:

1. Applied Mathematics and Computational Science (AMCS)
2. Bioscience (B)
3. Chemical and Biological Engineering (CBE)
4. Chemical Science (ChemS)
5. Computer Science (CS)
6. Earth Science and Engineering (ErSE)
7. Electrical Engineering (EE)
8. Environmental Science and Engineering (EnSE)
9. Marine Science and Engineering (MarSE)
10. Materials Science and Engineering (MSE)
11. Mechanical Engineering (ME)

Each program is administered by a Graduate Committee and a Graduate Chair. Courses for each program will be listed at the 100, 200, 300 or 400 level and designated as follows:

100 level: Remedial courses
200 level: M.S. program courses
300 level: Ph.D. program courses
400 level: Advanced seminars

<u>Grading</u>

Grading is based on a 9.0-point system as follows:

A+	=	9.0	B-	=	4.0
A	=	8.0	C+	=	3.0
A-	=	7.0	C	=	2.0
B+	=	6.0	C-	=	1.0
B	=	5.0	D	=	0

2. KAUST CURRICULUM DEFINITIONS

Semester system (Fall, Spring, Summer*)

*Summer is optional

1 Semester = 14 weeks (net) of classes

1 Week = 5 class days

1 Credit = 1 class/week = 14 classes/semester

1 Class = 50 minutes of lecture = 90 minutes of lab session

A course can have a weight of 3 credits (standard course), or any number of credits depending on the weight attributed to the course. A non-technical elective can have a weight of zero.

Syntax of course credit designation (examples):

A standard course comprising 3 lecture classes per week = (3-0-3)**

A standard course comprising 2 lecture classes and 1 lab session = (2-1-3)

A seminar course comprising no lectures = (0-0-1)

**Any course without a designation is considered a standard course (3-0-3)

3. MASTER'S PROGRAM DEGREE REQUIREMENTS

Admissions:
Admission to the M.S. program requires the satisfactory completion of an undergraduate B.S. degree in a relevant or related area, such as Engineering, Mathematics or the Physical, Chemical and Biological Sciences.

Requirements:
Thirty (30) credit hours must be completed in graduate-level courses and directed research projects. These courses should be 200-level or above, and they must be approved by the program advisor.

1. At least twenty-four (24) credit hours must be earned in technical courses.

2. At least nine (9) credit hours must be earned from a major track.

3. At least three (3) credit hours must be earned in mathematics courses.

4. At most six (6) credit hours may be earned in Winter Enhancement (WE) courses.

5. At most six (6) credit hours may be earned in directed research projects.

6. **The course grade must be B- or better for the credit hours received in any course to be counted toward any master's requirement.**

Cognates:
In order to ensure sufficient breadth of study, master's and doctoral students must satisfy a cognate requirement of at last one graduate course for a minimum of 3 hours of credit in areas outside one's own field.

Course Transfer and Equivalency:
Graduate credit hours **transferred** from other programs may be applied to meet any master's requirement.

Graduate courses taken from another university or program that are **equivalent** in level and content to the designated courses **in a major track** may be counted toward meeting the major track requirement if their equivalence is confirmed by the graduate chair.

Policy for Dropping Courses:
A course may be dropped without penalty or changed to visitor status at any time during the first eight weeks of the semester.

After the eighth week of a full semester, courses may be dropped or changed to visitor status only under exceptional circumstances and with the approval of the course instructor and the program chair.

4. DOCTORAL PROGRAM DEGREE REQUIREMENTS

The program is administered by the graduate committee representing faculty in the program. Doctoral qualification decisions are made by the Doctoral Qualification Committee comprised of all faculty members in the program.

Overview of Doctoral Requirements:
The doctoral degree (Ph.D.) is conferred by KAUST in recognition of marked ability and scholarship in some relatively broad field of knowledge, plus the demonstrated ability to carry out independent research yielding significant original results.

The doctoral program proceeds in three stages:

a. Qualification, marked by completion of the Preliminary Exam Part I: Qualification;
b. Candidacy, marked by completion of coursework and Preliminary Exam Part II: Research; and
c. Proposing, writing and defending the dissertation, marked by the Thesis Proposal Presentation and the Final Oral Defense.

Qualification marks the beginning of the doctoral program; *candidacy* signifies that course work is essentially completed and that a specific research area has been selected; successful definition, completion and defense of the doctoral dissertation in the *Final Oral Defense* mark the completion of the requirements for the Ph.D. degree.

Doctoral Qualifications:
To qualify for the doctoral program a student must do the following:

a. Satisfactorily complete the doctoral qualification coursework;
b. Initiate and make satisfactory progress in a research-oriented directed study project;
c. Take the doctoral Preliminary Examination Part I; and
d. Be accepted by the Doctoral Qualification Committee as qualified for doctoral study.

The decision to approve a student for doctoral study is made by the Doctoral Qualification Committee, which meets for this purpose after each offering of the Preliminary Examination Part I. All students who have just taken the examination are considered. The decision is based on the performance in the doctoral qualification coursework, Preliminary Examination Part I, the overall academic record as measured by the graduate's GPA and English proficiency. For each student the possible outcomes of the decision are:

a. Qualified for the doctoral program (for students with minor deficiencies in English proficiency, there may be a requirement to satisfactorily complete certain English-language courses);
b. Not qualified for the doctoral program, but allowed to retake the Preliminary Examination Part I (the committee will normally encourage or discourage such students); or

c. Not qualified for the doctoral program, and not allowed to retake the Preliminary Examination Part I.

A student may take the Preliminary Examination Part I and be considered for acceptance at most twice. It is offered two times per year: in the second and third full weeks of classes in the Fall and Spring semesters.

Students entering the program with a bachelor's degree are strongly encouraged to take the exam in the last semester of their M.S. degree program, and **must qualify** for the doctoral program within twenty-five (25) months of their entry into the graduate program. Students entering the Ph.D. program with a relevant master's degree are encouraged to take the Preliminary Examination Part I within thirteen (13) months of their entry and **must qualify** for the doctoral program within seventeen (17) months. These time periods include all semesters, and apply regardless of the semester in which graduate study begins.

The Academic and Research Advisors:
The academic advisor is determined by the major track of the student, and is particularly important for assistance in course planning at the beginning of a student's Ph.D. program. Each major track has at least one faculty member advisor, who will have extra office hours at the time of registration for classes for the next semester and will be available to the student to help plan for course registration and to answer academic questions. As the student progresses and becomes more involved with research, the research advisor will play a greater role in choosing courses and advising the student, but the student should continue to see the academic advisor to be sure that all degree requirements will be met.

Equivalency:
Graduate courses taken in other departments or universities that are equivalent in level and content to courses in a track may be counted toward that track. The decision to accept such courses is made by the graduate committee upon petition by the student. Students entering with a master's degree must submit such petitions as part of the planning and counseling process at the beginning of their first semester in the graduate program. Courses taken as an undergraduate are eligible for equivalency provided they can be taken for graduate credit at the host institution.

Students entering graduate studies with a master's degree may satisfy the doctoral coursework requirements by petitioning to have courses taken elsewhere counted toward their major track (through equivalency as described above) and by taking the necessary courses here. Regardless of the number of equivalent courses granted, such students shall complete:

At least nine (9) credit hours of graded program graduate courses prior to taking the Preliminary Examination Part I.

It is important for such students to obtain equivalency for previous courses so that they will be able to meet the Ph.D. timetable requirements.
Cognate Requirement:

In order to ensure sufficient breadth of study, KAUST requires graduate students to satisfy a cognate requirement of at least one graduate-level course for a minimum of three credit hours in areas outside of one's own field.

Courses taken elsewhere as part of a master's degree program or other graduate studies may be used provided they are outside the student's major area, are of graduate level, appear on the student's official graduate school transcript and were graded by a letter grade of B (or the equivalent) or higher. These courses do not have to be formally transferred.

GPA Requirements:
"Satisfactory" performance in the doctoral coursework means that the student must achieve at least a B grade in each course of the doctoral coursework, at least a 6.66 grade-point average in the courses he or she selects to satisfy the major track requirements.

Special Courses:
New graduate courses are often offered initially under a specific course number. If you wish to use one of these to satisfy a track requirement, you must obtain written approval from the instructor and the academic advisor in the track area of the course. This approval must be turned into the graduate secretary before submitting the Ph.D. Plan of Study for the qualification exam or for candidacy, and it will be placed in your graduate file.

Course Status Changes:
After the eighth week of a full semester, courses may be dropped or changed to visitor status only under exceptional circumstances and with the approval of the course instructor and Graduate Committee chair.

Ph.D. Plan of Study for Qualification and Candidacy:
The Ph.D. Plan of Study is intended to help you select courses and will ensure that you have an academic program that meets the Ph.D. coursework requirements. The Plan of Study will also make it easier for you and your advisors to plan a sequence of courses that meets your professional objectives. To help you get the best possible counseling, you will see the same academic advisor each time you need to work out your program, make election changes or simply need a chance to receive counsel from someone familiar with your intended area of specialization. As you get more involved with research, you should also consult with your research advisor about course planning. For students who enter with a bachelor's degree, the Ph.D. Plan of Study will be a continuation of their master's degree Plan of Study.

Each Ph.D. student must initiate a Ph.D. Plan of Study at the time when the student begins the Ph.D. program, and an up-to-date copy must be submitted when the student signs up to take the Preliminary Examination Part I. The Plan of Study must contain a listing of the courses the student has taken or intends to take to satisfy the qualification coursework requirements and must constitute a coherent program at an appropriate level. In addition, election worksheets for registration must be signed by the student's academic advisor. It is the student's responsibility to ensure that all requirements are met, and seeing the advisor will guarantee that no requirements are overlooked. Any departure from the requirements must be explicitly requested by written petition to the Graduate Committee.

You must have a rough-draft version of your Ph.D. Plan of Study when you receive counsel from your academic advisor. Your advisor will discuss your intended plan with you.

The Ph.D. Plan of Study is amenable to changes. It can be started while working on your master's degree. You should consult with your advisors to be absolutely certain that your Plan of Study will enable you to meet the coursework requirements by your desired timetable date.

The Ph.D. Plan of Study is used by the program chair to determine if the student has satisfied the track course requirements and the cognate requirements at the time the student wishes to advance to candidacy. At that time, the student must submit a copy of the Ph.D. Plan of Study for evaluation.

Research-Oriented Directed Study:
A Ph.D. aspirant must demonstrate his/her potential for conducting original research. This may be accomplished by doing a research-oriented directed study project for at least three (3) credit hours. The project need not be finished before taking Preliminary Exam Part I. If it is not finished, then, at least three weeks prior to taking the exam, the student is required to submit a **one-page progress report**, and the faculty advisor submits a separate evaluation to the Doctoral Qualification Committee indicating if the project is progressing satisfactorily. If the project is completed before taking Preliminary Exam Part I, a formal written report is submitted for the directed study project in lieu of the one-page progress report.

The completed project report and final faculty evaluation are required for admission to candidacy.

Doctoral Preliminary Examination Part I: Qualification:
The Preliminary Examination Part I is an oral examination whose purpose is to evaluate the student's ability to interrelate various topics and concepts, to analyze problems and to synthesize solutions.

The Preliminary Examination Part I is offered in the second and third full week of classes in the Fall and Spring semesters. At least 10 weeks prior to the examination, the student must indicate in writing his/her intention to take the examination. The Preliminary Examination Part I will be administered by an Examining Committee consisting of faculty members appointed by the Graduate Committee. Following the examination, each member of the Examining Committee will submit an evaluation of the student's performance to the Doctoral Qualification Committee.

The time at which the examination is taken is independent of the completion of the master's degree and the directed study. The time is determined by the time of completion of the M.S. major track requirement and it must satisfy the timetable given later in this section.

Part II of the Preliminary Examination is related to completion of the directed study project and is described later in this section.

English Proficiency:
As part of the qualifying process, the student's English proficiency will be evaluated, based on the performance in the Preliminary Examination Part I and the research-oriented directed study. Students deemed to have minor deficiencies in English, but who are otherwise qualified for the doctoral program, will be judged qualified for the doctoral program but will be required to perform satisfactorily in specified English-language courses. Students deemed to have major deficiencies in English will be judged not qualified for the doctoral program. Non-native English speakers are urged to achieve proficiency in English as early in their studies as possible.

The Research Advisor:
Shortly after a student has qualified for the doctoral program, the Graduate Committee shall appoint a research advisor who will guide the student toward candidacy. This includes completion of the directed study project, and therefore, in many cases, the advisor will be the directed study advisor. It is the responsibility of the student to find a faculty member willing to serve in this role and to propose him/her to the Graduate Committee for approval. In most cases the advisor will eventually become the dissertation advisor. Note: This advisor is distinct from the academic advisor associated with the student's major area. The academic advisor must still be consulted at the beginning of each term, and is the person who must sign all election worksheets.

CANDIDACY

Admission Criteria and Procedures:
A student will be admitted to candidacy when the following requirements have been met:

a. The student has completed all essential coursework including the doctoral candidacy coursework; and
b. The student has completed the directed study project.

Doctoral Candidacy Coursework:
As part of the process of achieving candidacy, a doctoral student must complete a set of courses known as the doctoral candidacy coursework. It includes at least thirty-six (36) credit hours of relevant graduate coursework beyond the bachelor's degree, of which at least eighteen (18) credit hours must have been earned at KAUST. (Students who enter the Ph.D. program with a relevant master's degree from another school will generally have had approximately eighteen (18) hours of relevant graded coursework, which gives a total of thirty-six (36) hours when combined with the required eighteen (18) hours at KAUST.)

In addition, the student must take sufficient courses from the chosen major track to satisfy certain requirements. These are listed for each program.

Students who change their major track from that used for their master's degree to a new track for their Ph.D. degree may have to take more than 36 hours to fulfill the course requirements.

Courses taken from other departments or universities that are equivalent in level and content to courses in a track may be counted toward that track. The decision to count such courses is made by the Graduate Program Committee upon petition by the student. Courses for which equivalency is given do not count toward the 18- or 36-hour requirement.

The cognate requirement must be completed before advancement to candidacy.

A copy of the Ph.D. Plan of Study must be completed and submitted to the graduate chair at the time the student applies for candidacy. This Plan of Study is used to verify that the candidacy coursework and hour requirements are satisfied. A student may apply for candidacy as soon as the coursework and directed study are complete.

Doctoral Preliminary Examination Part II: Research:
A student who has passed the Preliminary Examination Part I may proceed to candidacy as soon as the coursework for candidacy and the directed study project are completed. The directed study project requires a total registration of at least three (3) credit hours, which may be spread over one or more terms. To complete the directed study project, a formal written report is submitted to the supervisory faculty member (the research advisor) who supervises the project. The faculty member will provide a written evaluation to the Graduate Committee along with a copy of the report. A final grade of S (satisfactory) or U (unsatisfactory) will be given to the project by the research advisor.

In the event of an unsatisfactory grade in the project, the Graduate Committee will appoint a project review committee of three faculty members in the research area of the project but not including the research advisor. This committee will independently review the written report and examine the student's understanding of it in an oral exam. The committee may agree with the evaluation of the advisor, in which case the student is not advanced to candidacy, or it may disagree and the student is given time to improve the project or do a second project with a different advisor. Failure to complete this within the required timetable may result in disqualification from the Ph.D. program. It is the student's responsibility to find a faculty member to supervise a second project.

DISSERTATION

The Thesis Proposal Presentation and Dissertation Committee:
After admission to candidacy, it is the responsibility of the student to find an eligible faculty member willing to serve in this role and to propose him/her to the Graduate Committee for approval. In most cases the dissertation chair will be the same person who supervised the directed study project.

After appointment of the dissertation chair, the student will write a dissertation research proposal under the guidance of the dissertation chair and give a *Thesis Proposal Presentation*.

Upon satisfactory completion of the proposal, the student, in consultation with the dissertation chair, will recommend a tentative Dissertation Committee to the Graduate Committee. The dissertation chair (or co-chair) will be the chair (or co-chair) of the committee, which shall include at least three other members. The dissertation chair, or at least one of the co-chairs, must be from the program faculty. At least one member must be from outside the program. Eligibility for service as a dissertation chair or as a Dissertation Committee member must be consistent with KAUST rules. The tentative Dissertation Committee may be changed completely or in part after the *Thesis Proposal Presentation* if so desired by the student, dissertation chair or the Graduate Committee. The final decision on Dissertation Committee membership is made by the Graduate Committee.

See the graduate coordinator for the thesis proposal form that you must complete and have approved by the Graduate Committee. When the Dissertation Committee is formed, the student will submit the dissertation research proposal to the committee at least two weeks in advance of the *Thesis Proposal Presentation*.

The student will make an oral presentation of the proposal dissertation research, including relevant background material. During and after the presentation, the committee will explore the research project with the student in order to provide guidance and make an evaluation of its suitability. They will report to the Graduate Committee one of two results:

a. The student has presented an acceptable thesis proposal; or
b. The student does not have an acceptable proposal.

In the second case, the student must take immediate steps to refine the proposal in consultation with the chair and other committee members. It is the responsibility of the student to work with the committee, possibly augmented by other faculty members, to obtain an acceptable proposal within the time period given in the timetable given at the end of this section.

The *Thesis Proposal Presentation* requirement is completed when the Dissertation Committee chair reports a successful proposal presentation to the Graduate Office.

Following acceptance of the thesis proposal, the Dissertation Committee is finalized. This must be done within the timetable given later for the *Thesis Proposal Presentation*. The student submits a written request to the Graduate Committee with a proposed committee. Upon approval by the Graduate Committee, its membership is submitted to the Director of the Degree Programs in the Provost Office for approval. *Failure to finalize this committee until just before the Final Oral Defense may result in serious delays of the defense*. It is expected that the Dissertation Committee will regularly review the student's progress.

A person who is not a member of the graduate faculty of KAUST may serve on the Dissertation Committee with prior approval of the Graduate Committee. Such a person must have an earned doctorate or the equivalent.

It is expected that work on the thesis proposal will be done concurrently with the completion of coursework for candidacy.

The Dissertation and Its Defense: Final Oral Defense:
Upon completion, the dissertation must receive a written evaluation from each member of the Dissertation Committee and must be defended orally in an open examination before the committee. Following the successful *Final Oral Defense*, the student must consult with the dissertation chair(s) about any changes required by the committee, and must make these changes before final submission of the thesis to the Director of Degree Programs in the Provost Office.

SUMMARY OF THE TIMETABLE FOR THE Ph.D. PROGRAM

The following time periods include Fall and Spring semesters. They apply to all students regardless of the semester in which they begin graduate studies.

Any departure from the timetable must be explicitly requested in writing.

Students entering the graduate program with a bachelor's degree must:

1. Qualify for the doctoral program within twenty-five (25) months of entry. (For satisfactory progress, students are strongly encouraged to take the Preliminary Examination Part I during the last semester of the M.S. degree program.)
2. Complete Part II of the Preliminary Examination and achieve candidacy within 36 months of entry. (For satisfactory progress, candidacy should be achieved within 32 months.)
3. Complete the Thesis Proposal Presentation within 40 months of entry. (For satisfactory progress, the proposal should be completed within 36 months.)
4. Complete the dissertation and Final Oral Defense within six years of entry. (Under normal conditions the dissertation should take an average of four and a half years from entry to completion.)

Students entering the graduate program with a relevant master's degree must:

1. Qualify for the doctoral program within seventeen (17) months of entry. (For satisfactory progress, such students are strongly encouraged to take the Preliminary Examination Part I within thirteen (13) months.)
2. Complete Part II of the Preliminary Examination and achieve candidacy within twenty-eight (28) months of entry. (For satisfactory progress, candidacy should be achieved within 24 months.)
3. Complete the Thesis Proposal Presentation within thirty-two (32) months of entry. (For satisfactory progress, the proposal should be completed within 28 months.)
4. Complete the dissertation and Final Oral Defense within four years of entry. (Under normal conditions the dissertation should take an average of three years from entry to complete.)

Experience has shown that successful doctoral students devote a majority of their time to their academic program. Consequently, this timetable applies to all students, including those carrying outside obligations. Any departure from the timetable must be explicitly requested by written petition. Each petition will be reviewed by the Graduate Committee, and each decision will be made on the individual merits of the petition. The program may terminate the enrollment of any student who fails to follow these procedures and the timetable.

5. APPLIED MATHEMATICS AND COMPUTATIONAL SCIENCE PROGRAM

The Applied Mathematics and Computational Sciences (AMCS) program prepares students for success in constructing computational solutions to mathematical problems in a variety of areas. This preparation emphasizes the fundamentals of modeling, analyzing and computationally solving problems in many disciplines. The program in AMCS offers four tracks, each of which leads to a frontier of computational mathematics. The four track areas are:

- Partial Differential Equations (PDEs)
- Operations Research (OR)
- Information Science (IS)
- Modeling and Numerical Simulation (MNS)

A student seeking a degree in Applied Mathematics and Computational Sciences must specify one track area as a major. For the M.S. degree, course requirements include four designated Core courses, as well as a minimum of three Immersion courses and one Specialty course from the student's chosen major area. Additional elective coursework to meet the credit requirements for the degree gives students the flexibility to pursue further breadth and/or depth in their program. Each course carries 3 credit hours.

The M.S. degree requirement is 30 credits (generally comprised of 10 courses). Typically, students will take 12 credits (4 courses) per semester in the program, completing the M.S. program in 3 semesters (1.5 years).

Students pursuing a Ph.D. must first satisfy the coursework requirements for the M.S. program, take at least 6 additional credits (for a minimum of 12 courses overall), pass qualifying examinations and pursue original research culminating in a doctoral dissertation. Ph.D. coursework in AMCS includes diversity requirements in a particular domain of application and in computer science, ensuring that graduates are equipped to lead multidisciplinary research in which they are required to communicate in the language of and understand the intellectual culture of each contributing discipline—from formulation, to mathematical technique, to computational implementation, to analysis and interpretation of results. Completing the Ph.D. program generally takes 3 additional years beyond the completion of the M.S. program requirements. Further details on degree coursework requirements as well as Ph.D. program qualification and requirements are described in Section 4.

The Core courses required for all students in the AMCS program include:

- Linear Algebra with Applications (AMCS 200)
- Partial Differential Equations in Engineering (AMCS 204)
- Numerical Optimization (AMCS 304)
- Stochastic Methods in Engineering (AMCS 308)

The Immersion courses in each AMCS track are as follows:

Partial Differential Equations

- Introduction to Numerical Methods for Engineering (AMCS 206)
- Numerical Solution of Partial Differential Equations (AMCS 306)
- Applied Mathematics in the Chemical and Biological Sciences (AMCS 330)

Operations Research

- Combinatorial and Mathematical Programming (AMCS 208)
- Linear and Nonlinear Optimization (AMCS 211)
- Machine Learning (AMCS 229)
- Introduction to Stochastic Differential Equations (AMCS 236)
- Algorithmic Paradigms (AMCS 261)

Information Science

- Combinatorial and Mathematical Programming (AMCS 208)
- Machine Learning (AMCS 229)
- Information Networks (AMCS 337)
- Computational Methods in Data Mining (AMCS 340)

Modeling and Numerical Simulation

- Introduction to Stochastic Differential Equations (AMCS 236)
- Applied Mathematics in the Chemical and Biological Sciences (AMCS 330)
- Information Networks (AMCS 337)
- Computational Methods in Data Mining (AMCS 340)

The Specialty courses in the AMCS program are specified by individual faculty members and may vary from year to year.

APPLIED MATHEMATICS AND COMPUTATONAL SCIENCE (AMCS) COURSE DESCRIPTIONS

Note: AMCS courses listed below include cognates of some courses in the Computer Science (CS) program.

AMCS 100. Vector Calculus for Engineers (3-0-3) Computation and visualization using MATLAB. Differential vector calculus: analytic geometry in space, functions of several variables, partial derivatives, gradient, unconstrained maxima and minima, Lagrange multipliers. Integral vector calculus: multiple integrals in Cartesian, cylindrical and spherical coordinates; line integrals; scalar potential; surface integrals; Green's, divergence and Stokes' theorems. Examples and applications drawn from various engineering fields.

AMCS 101. Programming Methodology and Abstractions (3-0-3) (Same as CS 101.) Computer programming and the use of abstractions. Software-engineering principles of data abstraction and modularity. Object-oriented programming, fundamental data structures (such as stacks, queues, sets) and data-directed design. Recursion and recursive data structures (linked lists, trees, graphs). Introduction to basic time and space complexity analysis. The course teaches the mechanics of the C, C++ or Java language. This course is considered remedial training for students in the AMCS program and will not count toward any degree requirement.

AMCS 102. Ordinary Differential Equations for Engineers (3-0-3) *Prerequisite: AMCS 100.* Analytical and numerical methods for solving ordinary differential equations arising in engineering applications: solution of initial- and boundary-value problems, series solutions, Laplace transforms and non-linear equations; numerical methods for solving ordinary differential equations, accuracy of numerical methods, linear stability theory, finite differences. MATLAB programming as a tool kit for computations. Problems from various engineering fields.

AMCS 104. Linear Algebra and Partial Differential Equations for Engineers (3-0-3) *Prerequisite: AMCS 102.* Linear algebra: matrix operations, systems of algebraic equations, Gaussian elimination, undetermined and overdetermined systems, coupled systems of ordinary differential equations, eigensystem analysis and normal modes. Fourier series with applications, partial differential equations arising in science and engineering, analytical solutions of partial differential equations. Numerical methods for partial differential equations: iterative techniques, stability and convergence, time advancement, implicit methods, von Neumann stability analysis. Examples and applications from various engineering fields.

AMCS 106. Introduction to Probability and Statistics for Engineers (3-0-3) *Prerequisite: AMCS 100.* Probability: random variables, independence and conditional probability; discrete and continuous distributions, moments, distributions of several random variables. Topics in mathematical statistics: random sampling, point estimation, confidence intervals, hypothesis testing, non-parametric tests, regression and correlation analyses; applications in engineering, industrial manufacturing, medicine, biology and other fields.

AMCS 108. Introduction to Scientific Computing (3-0-3) *Prerequisite: AMCS 100.* This course covers numerical computation for mathematical, computational and physical sciences and engineering: numerical solution of systems of algebraic equations, least squares, quadrature, minimization of a function, banded matrices, nonlinear equations, numerical solution of ordinary and partial differential equations; truncation error, numerical stability for time-dependent problems, stiffness, boundary-value problems.

AMCS 154. Introduction to Automata and Complexity Theory (3-0-3) (Same as CS 154.) *Prerequisites: working knowledge of basic discrete mathematics (e.g., sets and functions) and proof techniques.* Regular sets: finite automata, regular expressions, equivalences among notations, methods of proving a language not to be regular. Context-free languages: grammars, pushdown automata, normal forms for grammars, proving languages non-context-free. Turing machines: equivalent forms, undecidability. Nondeterministic Turing machines: properties, the class NP, complete problems for NP, Cook's theorem, reducibilities among problems.

AMCS 157. Logic and Automated Reasoning (3-0-3) (Same as CS 157.) *Prerequisite: working knowledge of basic discrete mathematics (e.g., sets and functions) and proof techniques.* An elementary exposition from a computational point of view of propositional and predicate logic, axiomatic theories and theories with equality and induction. Interpretations, models, validity, proof, strategies and applications. Automated deduction: polarity, skolemization, unification, resolution, equality.

AMCS 161. Design and Analysis of Algorithms (3-0-3) (Same as CS 161.) *Prerequisite: solid computer programming skills (at least at the level of AMCS 101) and knowledge of probability (AMCS 106).* Efficient algorithms for sorting, searching and selection. Algorithm analysis: worst- and average-case analysis. Recurrences and asymptotics. Data structures: balanced trees, heaps, hash tables. Algorithm design techniques: divide-and-conquer, dynamic programming, greedy algorithms, amortized analysis. Algorithms for fundamental graph problems such as depth-first search, connected components, topological sort and shortest paths. Possible additional topics: network flow, string searching, parallel computation.

AMCS 171. Real Analysis (3-0-3) *Prerequisite: AMCS 100.* The development of real analysis in Euclidean space: sequences and series, limits, continuous functions, derivatives, integrals. Properties of Riemann integrals, continuous functions and convergence in metric spaces, compact metric spaces, basic point set topology.

AMCS 200. Linear Algebra with Applications (3-0-3) *Prerequisite: AMCS 100.* Direct and iterative methods to solve linear systems of equations arising in engineering applications. The theory of linear algebra: basis, linear independence, column space, null space, rank; round-off errors, pivoting and ill-conditioned matrices; norms and condition numbers; projections and least squares; eigenvalues, eigenvectors and their computation; the canonical diagonal form; functions of a matrix; solution of systems of nonlinear equations arising in engineering applications.

AMCS 204. Partial Differential Equations in Engineering (3-0-3) *Prerequisite: AMCS 200 (may be taken concurrently).* Geometric interpretation of partial differential equation (PDE) characteristics; solution of first-order PDEs and classification of second-order PDEs; self-similarity; separation of variables as applied to parabolic, hyperbolic and elliptic PDEs; special functions; eigenfunction expansions; the method of characteristics. If time permits, Fourier integrals and transforms, Laplace transforms.

AMCS 206. Introduction to Numerical Methods for Engineering (3-0-3) *Prerequisite: AMCS 200.* Numerical methods from a user's point of view. Lagrange interpolation, splines. Integration: trapezoid, Romberg, Gauss, adaptive quadrature; numerical solution of ordinary differential equations: explicit and implicit methods, multistep methods, Runge-Kutta and predictor-corrector methods, boundary-value problems, eigenvalue problems; systems of differential equations, stiffness. Emphasis is on analysis of numerical methods for accuracy, stability and convergence. Introduction to numerical solutions of partial differential equations, von Neumann stability analysis, alternating direction implicit methods and nonlinear equations.

AMCS 208. Combinatorial and Mathematical Programming (3-0-3) Combinatorial and mathematical programming (integer and non-linear) techniques for optimization. Topics: linear program duality and LP solvers; integer programming; combinatorial optimization problems on networks including minimum spanning trees, shortest paths and network flows; matching and assignment problems; dynamic programming; linear approximations to convex programs; NP-completeness. Hands-on exercises.

AMCS 211. Linear and Nonlinear Optimization (3-0-3) *Prerequisite: AMCS 200.* Optimization theory and modeling. The role of prices, duality, optimality conditions and algorithms in finding and recognizing solutions. Perspectives: problem formulation, analytical theory, computational methods and recent applications in engineering, finance and economics. Theories: finite dimensional derivatives, convexity, optimality, duality and sensitivity. Methods: simplex and interior-point, gradient, Newton and barrier.

AMCS 221. Artificial Intelligence (3-0-3) (Same as CS 221.) *Prerequisites: working knowledge of basic discrete mathematics (e.g., sets and functions) and proof techniques, programming ability (at least at the level of AMCS 101) and exposure to probability.* An introduction to the principles and practices of artificial intelligence. Topics include: search, constraint satisfaction, knowledge representation, probabilistic models, machine learning, neural networks, vision, robotics and natural-language understanding.

AMCS 229. Machine Learning (3-0-3) *(Same as CS 229.)* Prerequisites: linear algebra (comparable to AMCS 104) and basic probability and statistics (comparable to AMCS 106), AMCS *221.* Topics: statistical pattern recognition, linear and non-linear regression, non-parametric methods, exponential family, GLIMs, support vector machines, kernel methods, model/feature selection, learning theory, VC dimension, clustering, density estimation, EM, dimensionality reduction, ICA, PCA, reinforcement learning and adaptive control, Markov decision processes, approximate dynamic programming and policy search.

AMCS 236. Introduction to Stochastic Differential Equations (3-0-3)
Prerequisite: familiarity with stochastic processes and differential equations. Brownian motion, stochastic integrals and diffusions as solutions of stochastic differential equations. Functionals of diffusions and their connection with partial differential equations. Random walk approximation of diffusions.

AMCS 242. Programming Languages (3-0-3) (Same as CS 242.) *Prerequisites: programming experience with Lisp, C and an object-oriented programming language.* Central concepts in modern programming languages, impact on software development, language design trade-offs and implementation considerations. Functional, imperative and object-oriented paradigms. Formal semantic methods and program analysis. Modern type systems, higher-order functions and closures, exceptions and continuations. Modularity, object-oriented languages and concurrency. Runtime support for language features, interoperability and security issues.

AMCS 244. Computer Networks (3-0-3) (Same as CS 244.) *Prerequisite: AMCS 240.* Packet switching, Internet architecture, routing, router architecture, flow control algorithms, retransmission algorithms, congestion control, TCP/IP, detecting and recovering from errors, switching, Ethernet (wired and wireless) and local area networks, physical layers, clocking and synchronization. Assignments introduce network programming, including sockets, designing a router and implementing a transport layer.

AMCS 248. Computer Graphics (3-0-3) (Same as CS 248.) *Prerequisites: solid programming skills (at least at the level of AMCS 101) and linear algebra.* Input and display devices, scan conversion of geometric primitives, 2D and 3D geometric transformations, clipping and windowing, scene modeling and animation, algorithms for visible surface determination, local and global shading models, color and real-time rendering methods.

AMCS 261. Algorithmic Paradigms (3-0-3) (Same as CS 261.) *Prerequisite: AMCS 161.* Topics: algorithms for optimization problems such as matching, max-flow, min-cut and load balancing. Using linear programming, emphasis is on LP duality for design and analysis of approximation algorithms. Approximation algorithms for NP-complete problems such as Steiner trees, traveling salesman and scheduling problems. Randomized algorithms.

AMCS 304. Numerical Optimization (3-0-3) *Prerequisites: AMCS 200. Recommended: AMCS 171.* Solution of nonlinear equations. Optimality conditions for smooth optimization problems. Theory and algorithms to solve unconstrained optimization, linear programming, quadratic programming, global optimization, general linearly and nonlinearly constrained optimization problems. Programming project.

AMCS 306. Numerical Solution of Partial Differential Equations (3-0-3)
Prerequisites: AMCS 200, AMCS 204. Hyperbolic partial differential equations: stability, convergence and qualitative properties; nonlinear hyperbolic equations and systems; combined solution methods from elliptic, parabolic and hyperbolic problems. Examples include: Burgers' equation, Euler equations for compressible flow and Navier-Stokes equations for incompressible flow.

AMCS 308. Stochastic Methods in Engineering (3-0-3) *Prerequisite: AMCS 106.* Review of basic probability; Monte Carlo simulation; state space models and time series; parameter estimation, prediction and filtering; Markov chains and processes; stochastic control; and stochastic differential equations. Examples from various engineering disciplines.

AMCS 330. Applied Mathematics in the Chemical and Biological Sciences (3-0-3) *Prerequisite: AMCS 100, 102, 104.* Mathematical solution methods via applied problems including chemical-reaction sequences, mass and heat transfer in chemical reactors, quantum mechanics, fluid mechanics of reacting systems and chromatography. Topics include generalized vector space theory, linear operator theory with eigenvalue methods, phase plane methods, perturbation theory (regular and singular), solution of parabolic and elliptic partial differential equations and transform methods (Laplace and Fourier).

AMCS 337. Information Networks (3-0-3) *Prerequisite: basic probability and graph theory.* Network structure of the Internet and the Web. Modeling, scale-free graphs, small-world phenomenon. Algorithmic implications in searching and inter-domain routing, the effect of structure on performance. Game theoretic issues, routing games and network creation games. Security issues, vulnerability and robustness.

AMCS 340. Computational Methods in Data Mining (3-0-3) *Prerequisites: AMCS 106, AMCS 108.* Focus is on very-large-scale data mining. Topics include computational methods in supervised and unsupervised learning, association mining and collaborative filtering. Individual or group applications-oriented programming project. 1 unit without project; 3 units requires final project.

6. BIOSCIENCE PROGRAM

The Bioscience master's program is open to all KAUST graduate students subject to approval by their advisor. The curriculum provides a strong introduction with courses on the biochemistry and biophysics of living matter. Each course is a self-contained module providing a complete review of the subject concerned. Central to the M.S. program is the independent research project that provides an opportunity for students to explore their research interests hosted within KAUST PI laboratories.

The program comprises a single track of self-contained modules consisting of lectures, seminars and laboratory classes. There are two optional introductory/refresher courses, aimed at graduates moving into the bioscience field. The M.S. program is a single core of seven taught courses and an independent research project. Two advanced courses are offered as supplemental elements to the M.S. and Ph.D. programs. Further details on degree requirements as well as Ph.D. program qualification and requirements are described in Section 4.

Optional Courses:

B 101 Introduction to Engineering Bioscience (2-1-3)
B 102 Gene Structure and Function (2-1-3)

Core Master's Courses:

B 201 Biophysics (2-0-2)
B 202 Plant and Microbial Biodiversity (2-1-3)
B 203 Plant and Microbial Development (2-1-3)
B 204 Genomics (2-1-3)
B 205 Protein Structure and Function (2-1-3)
B 206 Synthetic Biology and Biotechnology (2-1-3)
B 207 Physiology and Metabolic Engineering (2-1-3)
B 208 Research Project (0-10-10)

Advanced Courses:

B 301 Computational Biology and Bioinformatics (2-1-3)
B 302 Visualization of Biological Systems (2-1-3)

BIOSCIENCE COURSE DESCRIPTIONS

B 101. Introduction to Engineering Bioscience (2-1-3) *Prerequisite: degree in biological sciences or engineering or consent of instructor.* Origin of life on earth, cellular plans and advantages/limitations imposed by cell designs. Membranes and transport, specialized transport protein structures. Protein structure. Central metabolism, amino acid synthesis. Energy metabolism ATP, ATP hydrolase. DNA, proteins and the genetic code. Introduction to molecular biology. Transcription and translation in prokaryotes and eukaryotes. Genome structure, introduction to genomics and bioinformatics. Gene control laboratory class

B 102. Gene Structure and Function (2-1-3) *Prerequisite: degree in biological sciences or engineering or consent of instructor.* Essentials of Mendelian and molecular genetics as the basis for current models of prokaryotic and eukaryotic genetic exchange and gene expression. Chromosome organization; mechanisms and consequences of recombination; gene organization, operons/regulons, control of transcription, translation and epigenetics. Data handling and problem solving; critical essays and discussion of literature.

B 201. Biophysics (2-0-2) *Prerequisite: degree in biological sciences or engineering or consent of instructor.* The course explores how the techniques, methods and general philosophy of the physical sciences can be applied to biology. It is concerned with the structure and organization of biological systems and has the cell at its center. From there, it extends both down to the molecular realm and upward to the tissue/organism level. In contrast to systems biology, which has an emphasis on models to accommodate and interpret large-scale information derived from high-throughput experiments, Biophysics will strive to understand the various levels of biological organization and the relationships which exist between them.

B 202. Plant and Microbial Biodiversity (2-1-3) *Prerequisite: degree in biological sciences or engineering or consent of instructor.* Review of cellular structure function, diffusion and active transport limitations and benefits on cell systems. Membrane structures translocation and transport. Energy and primary metabolism, secondary metabolism in microbes and plants. Chromosome structures. Genome composition, plasticity and evolution. Literature criticism, data handling and problem solving. Microbiological screening laboratory. Isolation and characterization of novel non-pathogenic soil bacteria with specific catabolic properties. Biological structures imaging laboratory. In situ staining and visualization of prokaryotic and eukaryotic cell structures.

B 203. Plant and Microbial Development (2-1-3) *Prerequisite: degree in biological sciences or engineering or consent of instructor.* Introduction to cell division and differentiation in microbes; sporulation and morphogenesis in bacteria; genetic switching of yeast mating type; slime mold development; algal and plant cells; molecular genetics of embryogenesis, polarity, symmetry breaking and self-organization; cell-cell signaling; genetics, biophysics and computer models. Hands-on access developmental mutants and analysis of phenotypes; applications in biotechnology. Literature criticism, data handling and problem solving.

B 204. Genomics (2-1-3) *Prerequisite: degree in biological sciences or engineering or consent of instructor.* Prokaryotic versus eukaryotic genome structure, conservation (gene order/sequence/structure, regulatory sequences), approaches to mapping/sequencing genomes, DNA sequencing, DNA sequencing technologies, approaches to genome annotation, SNPs, microarray technology, gene expression microarrays, antibodies, chromatin immuno-purification, high-throughput perturbation studies. Problem-solving/data-handling/critical-thinking/journal-club sessions. Possible interactions with Genomics Research Core facility.

B 205. Protein Structure and Function (2-1-3) *Prerequisite: degree in biological sciences or engineering or consent of instructor.* Introduction to protein structure and technologies used to study protein structure, X-ray crystallography, protein NMR. Protein folding, post translational modification, protein sorting. Enzyme structure and function. Study of differential protein expression, proteomics. Protein interactions, methods to study the interactome. Problem-solving/data-handling/critical-thinking/journal-club sessions. Possible interactions with Genomics Research Core facility.

B 206. Synthetic Biology and Biotechnology (2-1-3) *Prerequisite: degree in biological sciences or engineering or consent of instructor.* Introduction to genetic circuits in natural systems; engineering principles in biology; BioBricks and standardization of biological components; numerical methods for systems analysis and design; fabrication of genetic systems in theory and practice; transformation and characterization; examples of engineered systems; hands-on experiments.

B 207. Physiology and Metabolic Engineering (2-1-3) *Prerequisite: degree in biological sciences or engineering or consent of instructor.* Introduction to regulation of metabolism and physiology of microbes and plants; hands-on analytical techniques for measuring metabolite and ion levels; mechanisms for homeostasis; influence of environmental changes, including nutrition, salt stress, temperature and drought; genetic pathways for stress response and adaptation in plant and microbial systems, crop improvement and biotechnology. Gene expression and cell-based expression systems for protein and small molecules; gene cloning and expression laboratory; gene over-expression strategies. Biocatalysis and metabolic engineering.

B 208. Research Project (0-10-10) *Prerequisite: degree in biological sciences or engineering or consent of instructor.* Research project to be conducted during two semesters with a minimum of 12 hours per week in the second semester and full time in the third semester spent carrying out the project. Projects may be laboratory-based “wet” or a computational “dry.” Projects would be hosted in PI laboratories, AEA partner laboratories or other industrial or academic laboratories. The project will require a literature search of the relevant subject area, acquisition of data by research and the preparation of a dissertation. The examination of the project will be conducted by an oral presentation of the work by the candidate, followed by a *viva voce*.

B 301. Computational Biology and Bioinformatics (2-1-3) *Prerequisite: degree in biological sciences or engineering or consent of instructor.* Introductory programming (Perl, R), introduction to Unix operating systems, alignment algorithms, assembly algorithms, widely used programs and bio-computing packages, statistics, modeling, differential equations, matching hardware design to performance needs. Demonstrations, programming/problem-solving/data-handling/critical-thinking/journal-club sessions.

B 302. Visualization of Biological Systems (2-1-3) *Prerequisite: degree in biological sciences or engineering or consent of instructor.* Hands-on training in optical and electron microscopy; light microscopy: bright field, fluorescence and interference contrast modes; stains and labels; fluorescent proteins, image processing; quantitative imaging; 3D visualization and segmentation; FRET, FRAP, FCS,STED and FACS; transmission and scanning electron microscopy; staining and cryomicroscopy; tomography; scanning probe microscopy. Imaging project.

BIOSCIENCE LABORATORY REQUIREMENTS

Plant and Microbial Diversity (2-1-3) Microbiological screening laboratory. Isolation and characterization of novel non-pathogenic soil bacteria with specific catabolic properties. Biological structures imaging laboratory. In situ staining and visualization of prokaryotic and eukaryotic cell structures.

Plant and Microbial Development (2-1-3) Analysis of developmental mutants and phenotypes.

Genomics (2-1-3) Possible interactions with Genomics Research Core facility.

Protein Structure and Function (2-1-3) Possible interactions with Genomics Research Core facility

Research Project (0-8-8) Based in PI laboratories, internships, other KAUST institutes, AEA partners, GRP partners, other academic institutions, industrial partners.

Synthetic Biology and Biotechnology (2-1-3) Synthetic biology laboratory. Possible interaction with Genomics Research Core facility

Physiology, Metabolic and Process Engineering (2-1-3) Gene cloning and expression laboratory. Bioprocess laboratory.

Computational Biology and Bioinformatics (2-1-3) Programming/problem-solving/data-handling laboratory.

Visualization of Biological Systems (2-1-3) Imaging project laboratory.

7. CHEMICAL AND BIOLOGICAL ENGINEERING PROGRAM

The program has two major tracks, each consisting of 4 Core courses and 8 or more Electives. The two tracks together cover a broad range of modern advanced chemical and biological engineering and should equip a student for a successful and productive career in these fields.

The two tracks are:

- Advanced Chemical Engineering, including specializations in process systems engineering, energy engineering, product engineering and advanced process technology;

- Advanced Biological Engineering, including specializations in bioenergy, biotherapeutics and the environment.

A student seeking a degree in chemical and biological engineering must specify one track as a major, take the 4 Core courses and a minimum of 3 Elective courses in that track for the M.S. degree, and an additional 2 courses for the Ph.D. degree. All courses (including Core modules) on a track are available as Electives for students taking the other track. Each course carries 3 credit hours.

The M.S. degree requirement is 30 credit hours, and the Ph.D. requires a minimum of an additional 6 credit hours of course work and 24 hours of dissertation research. Typically, the duration of the M.S. program is 1.5 years, and the Ph.D. is 3 years beyond that. More detailed information on degree requirements, including qualifying, candidacy, dissertation and final defense, are described in Section 4.

The courses in each track are as follows:

<u>Advanced Chemical Engineering Core Courses</u>
CBE 201, CBE 202, CBE 203, CBE 204

<u>Advanced Chemical Engineering Electives</u>
CBE 211, CBE 212, CBE 213, CBE 214, CBE 215
CBE 216, CBE 217, CBE 218, CBE 236, CBE 237
CBE 311, CBE 312, CBE 313, CBE 314, CBE 315, CBE 334

<u>Advanced Biological Engineering Core Courses</u>
CBE 221, CBE 222, CBE 223, CBE 224

<u>Advanced Biological Engineering Electives</u>
CBE 231, CBE 232, CBE 233, CBE 234
CBE 235, CBE 236, CBE 237, CBE 238
CBE 331, CBE 332, CBE 333, CBE334

CHEMICAL AND BIOLOGICAL ENGINEERING PROGRAM COURSE DESCRIPTIONS

CBE 201. Applied Engineering Thermodynamics Applications of thermodynamics and molecular theory in chemical engineering. Fundamentals: thermodynamics of phase equilibria, volumetric properties, introduction to statistical thermodynamics, corresponding states. Techniques: equation of state theories, excess free-energy models, molecular simulation. Applications: high-pressure phase equilibria, polymers, electrolytes.

CBE 202. Transport Phenomena Fundamentals of fluid mechanics and the methodology required for the solution of flow problems. Conservation of mass: Lagrangian and Eulerian formulations, differentiation following the motion, continuity equation. Conservation of momentum: body and surface forces, stress, linear momentum; Navier equations; Navier-Stokes equations. Constitutive equations: rheology, deformation and rate of strain; constitutive equations; Newtonian and non-Newtonian fluids.

CBE 203. Reaction Engineering Advanced aspects of chemical reaction engineering: fundamentals of catalytic reactor design, especially heat and mass transfer with chemical reaction in gas-solid systems; design of fixed-bed catalytic reactors, multiphase, fluidized bed and transport reactors; fundamentals of non-catalytic fluid-solid reactions.

CBE 204. Engineering Mathematics and Numerical Methods Numerical linear algebra, the solution of linear and nonlinear algebraic systems of equations, the integration of nonlinear dynamic systems, the solution of partial differential equations, the use and solution of population balances, foundation of numerical methods in statistics, foundation of numerical methods in molecular simulation and computational fluid dynamics. Lectures and laboratory.

CBE 211. Dynamic Behavior of Process Systems Dynamic behavior of complex batch and continuous process engineering systems: modeling as lumped and distributed systems, estimation and validation of such models, the formulation and solution of dynamic process optimization problems for typical engineering problems. Lectures and laboratory.

CBE 212. Advanced Process Control Advanced control applications: the role of signals and measurements; the design of plant-wide control systems; the use, selection and evaluation of advanced control schemes; the use of data-driven approaches to analyze and control process behavior. Lectures and laboratory.

CBE 213. Interface Science, Engineering and Technology Fundamentals of colloid and interface science applied to rational formulation of structured products. Micro- and macro-structure properties of suspensions, surfactants, liquid-liquid and liquid-solid interfaces; characteristics of emulsions and foams, vesicles and liposomes, creams, pastes, granules and particles; processing and product characterization methods. Lectures and laboratory.

CBE 214. Electrochemical Engineering and Technology Principles, design and operation of electrochemical reactors and processes, fuel cells and batteries.

Electrode potentials and redox reactions; potential-pH and activity-pH diagrams for element-water systems; transport rates in electrochemical systems; kinetics of electrochemical reactions; functions and selection of electrode materials; catholyte/anolyte separators and ion-permeable membranes; design and modeling of electrochemical reactors; performance of reactors/processes, fuel cells and batteries.

CBE 215. Polymers and Polymerization Processes Cornerstones of polymer science: synthesis, characterization, processing and properties. Monomer synthesis, polymerization chemistry, reactors and scale-up, polymer structure (solution and solid state), morphology and “processability.” Lectures, case studies and laboratory.

CBE 216. Engineering of Sustainable Processes Environmental impacts of human activities, how to quantify such impacts; application of chemical engineering unit operations to emission abatement; concepts of sustainability, waste minimization, clean technology and green chemistry; factors which determine how emission legislation is approached and formulated; process safety and loss prevention.

CBE 217. Clean Fossil Fuels Types of fossil fuels, availability, emissions; CCS technologies; combustion technologies for power generation, pulverized coal, supercritical processes, fluidized beds, IGCC, oxyfuel; gasification and clean-up processes; gas for power and fuel, CCGT, LNG, oil for cleaner fuels, heavy and non-conventional oils; syngas production from gas, oil, coal, biomass; routes to syngas/hydrogen and liquid fuels.

CBE 218. Urban Energy Systems Urbanization and growth in energy demand; cities as dynamic systems; characterizing city infrastructures, complex systems and networks; energy supply, conversion and demand in cities; resource flows and city sustainability; modeling, analysis and optimization of cities from an energy systems perspective; transport modeling; land-use interactions and energy demand; case studies.

CBE 221. Biological Transport Phenomena Conservation of mass and momentum, physiological mass transport, membrane structure, carrier proteins and active membrane transport, ion channels, intracellular vesicular transport, diffusion in reacting systems, heat and mass transfer in bioreactors, culture aeration. Lectures and laboratory.

CBE 222. Bioprocess Fundamentals Genetic recombination, expression systems, principles of fermentation processes, bioreactor types and operation modes, process scale-up, separation and recovery of biological products. Industrially relevant applications, such as microbial systems, mammalian systems, stem cell systems. Lectures, case studies and laboratory.

CBE 223. Bio-Engineering Mathematics and Bio-Statistics Analyze and formulate bio-engineering problems in mathematical form, solve them and analyze the results. Numerical linear algebra, linear and nonlinear algebraic systems of equations, integration of nonlinear dynamic systems, partial differential equations, population balances, foundation of numerical methods in statistics, foundation of numerical methods in molecular simulation and computational fluid dynamics. Lectures and laboratory.

CBE 224. Fundamentals of Cell Biology Types of microorganisms (e.g., viruses, microbes, yeast, mammalian and stem cells); cell physiology, structure and function; gene expression and protein synthesis; protein folding; post-translational modification; cell cycle; molecular biology techniques. Lectures and laboratory.

CBE 231. Biological Separations Basic cell separation techniques such as filtration and centrifugation, cell rupture; purification techniques such as adsorption (affinity and ligand), chromatography, solvent extraction, precipitation and crystallization; process flowsheeting in downstream separation. The laboratory course will focus on analytical techniques and downstream unit operations in biotechnology. Lectures and laboratory.

CBE 232. Metabolic Engineering Fundamentals of redox reactions, catalysis and the use of energy by cells, enzyme-catalyzed reaction kinetics, glucose metabolism, regulation of metabolic pathways, respiration, anaerobic metabolism, autotrophic metabolism, principles of metabolic flux analysis.

CBE 233. Modeling of Biological Systems Homeostasis and physiology of healthy and disease states; modeling of feedback control mechanisms; cell signaling, including molecules, receptors and pathways; modeling of reaction networks; signal transduction modeling; cell cycle regulation; population modeling; gene expression control and regulation; metabolic flux analysis.

CBE 234. Biomechanics Tissue and cell mechanics; physiological fluid mechanics; stress, strain and deformation; mechanical properties and molecular structure; analysis of musculoskeletal systems.

CBE 235. Environmental Biotechnology Microbial and thermodynamic concepts and quantitative tools: stoichiometry and bacterial energetics; microbial kinetics; biofilm kinetics and reactors; application design: activated sludge and aerobic biofilm processes, nitrification, denitrification, phosphorus removal, anaerobic treatment and detoxification of hazardous chemicals. Lectures and laboratory.

CBE 236. Membrane Science and Membrane Separation Processes Formulation and solution of engineering problems involving design of membrane systems for gas separation, reverse osmosis, filtration, dialysis, pervaporation and gas absorption/stripping processes. Membrane selection, fabrication and preparation. Membrane transport: gas permeation and reverse osmosis. Polarization and fouling, membrane module design. Lectures and laboratory.

CBE 237. Pharmaceutical Process Development Methodology for the development of pharmaceutical and related processes and associated equipment design, main challenges in pharmaceutical process development, conceptual designs from process chemistry, design calculations for separation and isolation processes, experimental design, elucidation of reaction kinetics from experiments.

CBE 238. Biofuels Bioethanol and biodiesel; petrofuels vs. biofuels; outline of manufacturing: feedstocks, typical process configurations; operational and blending issues; advantages and drawbacks of biofuels; introduction to second-generation biofuels.

CBE 311. Advanced Process Optimization *Prerequisite: CBE 204*. Formulating and solution of problems in process synthesis, design and operations using advanced optimization methods. Mathematical modeling via mixed integer and continuous optimization formulations, principles of continuous optimization, principles of modeling with integer variables, principles of mixed-integer linear and nonlinear optimization, principles of optimization under uncertainty, applications to interactions of design and control and model-based control.

CBE 312. Advanced Transport Phenomena *Prerequisite: CBE 202*. Exact, approximate and semi-analytical solutions of the Navier-Stokes equations. Heat and mass transfer in natural and forced convection. Hydrodynamic instabilities: capillary and gravity waves, Rayleigh instability, Rayleigh-Benard and Benard-Marangoni convection. Turbulence: dimensional analysis, transitional and fully developed turbulent flows; Reynolds averaging and models for Reynolds stresses; CFD.

CBE 313. Dynamical Systems in Chemical Engineering. *Prerequisite: CBE 204*. Development and application of modern techniques in nonlinear dynamics, pattern formation and bifurcation theory. Analytical and numerical tools required for complex nonlinear dissipative dynamical systems. Multiple coexisting states and hysteresis, onset of oscillations, aperiodic and chaotic behavior, spontaneous breaking of spatial symmetry and pattern formation, nonlinear waves and turbulence.

CBE 314. Particle Engineering. Fundamentals: particle characterization, particle mechanics, population balances. Unit operations: particle formation, particle-fluid separation, size reduction, size enlargement, mixing and de-mixing, storage and transport.

CBE 315. Modeling of Phase Equilibria. *Prerequisite: CBE 201*. Predicting the phase behavior of fluids in the context of process design: theoretical fundamentals and modern computational methods including advanced thermodynamic models and molecular simulation techniques. Lectures and case studies.

CBE 331. Tissue Engineering and Stem Cells. *Prerequisite: CBE 224*. Principles of regenerative medicine, cellular engineering, mesenchymal and embryonic stem cells, pluripotency, controlled differentiation, growth factors, cell encapsulation, scaffolds, techniques for product characterization, principles of stem cell bioprocesses, examples of applications (e.g., cartilage, bone, cardiomyocytes). Lectures and laboratory.

CBE 332. Materials for Bio-Applications. Selection, fabrication/processing and testing of biomaterials; scaffolds for applications in tissue engineering and regenerative medicine; examples of applications in lung, bone and soft-tissue engineering; biodegradable polymers; injectable scaffolds; surface modification.

CBE 333. Biomass and Bio-Refineries. Common types and chemical composition of biomass; processes to convert biomass to added-value chemicals, materials, fuel, power and other products; examples of gasification, fermentation, digestion and pyrolysis methods; treatment of extracted material.

CBE 334. Formulation Engineering and Technology. Scientific fundamentals and engineering practice of liquid and solid products formulation; selection of ingredients and processing routes for formulated products in the pharmaceutical, consumer goods, cosmetics, foods and specialty chemicals sectors. Lectures and laboratory.

8. CHEMICAL SCIENCE PROGRAM

The programs leading to the M.S. or Ph.D. degree in Chemical Science emphasize the attainment of a high level of competency in one of four specialized areas of chemistry, each represented by a separate track of study. The four tracks cover the major classical divisions of Chemical Science: Analytical, Inorganic, Organic and Physical Chemistry. By completing the M.S. degree, the student will have acquired a sound foundation for a career in chemical research or for continuing advanced graduate studies.

The major emphasis for the Ph.D. degree is on research. The program leading to the Ph.D. degree requires the development of a broad knowledge through additional coursework beyond the M.S. requirement and through supervised research. Upon completion of the Ph.D. degree, the student is expected to be capable of designing and executing independent research projects.

A student seeking either a master's or a doctorate in the Chemical Science must select one of the following four program tracks:

- Analytical Chemistry
- Inorganic Chemistry
- Organic Chemistry
- Physical Chemistry

A student seeking a master's degree in the Chemical Science program must specify one track as a major and complete a minimum of three courses in that track at or above the 200 level. The M.S. degree requirement is 30 credit hours, of which 15 credit hours must be taken in Chemical Science. A student pursuing a doctoral degree must complete five courses in the chosen track, at least two of which must be at the 300 level or above. The Ph.D. requires a minimum of 36 credit hours of coursework, at least 21 of which are taken in Chemical Science. Further details on degree coursework requirements as well as Ph.D. program qualification and requirements are described in Section 4.

The courses in each track are as follows:

<u>Analytical Chemistry</u>:
ChemS 250, ChemS 365, ChemS 370, ChemS 375, ChemS 420

<u>Inorganic Chemistry</u>:
ChemS 200, ChemS 210, ChemS 220, ChemS 350, ChemS 360
ChemS 410, ChemS 440

<u>Organic Chemistry</u>:
ChemS 220 ChemS 230, ChemS 240, ChemS 330, ChemS 335
ChemS 340, ChemS 345, ChemS 400, ChemS 450

<u>Physical Chemistry</u>:
ChemS 260, ChemS 265, ChemS 270, ChemS 300, ChemS 325
ChemS 350, ChemS 355, ChemS 360, ChemS 380, ChemS 430

CHEMICAL SCIENCE PROGRAM COURSE DESCRIPTIONS

ChemS 150. Physical Methods of Analysis (3-0-3) The course introduces the student to the principles and techniques of modern analytical chemistry. Atomic and molecular spectroscopy, mass spectrometry and chromatographic separation techniques are stressed. Some discussion of contemporary electrochemistry is included. The principles of data collection and the processing and representation of analytical signals are introduced.

ChemS 160. Introductory Physical Chemistry (3-0-3) This course provides an introduction to quantum mechanics and its application to chemistry. The Schrödinger equation is solved in one, two and three dimensions for important chemical problems. Group theory and quantum chemistry are used to understand chemical bonding and advanced spectroscopy.

ChemS 170. Molecular Physical Chemistry (3-0-3) Designed for non-specialists lacking a solid background in physical chemistry. Applications of wave mechanics to exactly solvable problems. Elementary applications of operators, symmetry and group theory. Electronic structure of atoms and molecules. Principles of molecular spectroscopy.

ChemS 180. Chemical Thermodynamics (3-0-3) Designed for non-specialists lacking a solid background in physical chemistry. A discussion of chemical phase equilibria, the treatment of solutions and chemical reactions by classical thermodynamics, the applications of electrochemical cells in studying chemical reactivities, utilization of molecular and atomic spectra in statistical-mechanical calculations.

ChemS 200. Inorganic Chemistry (3-0-3) *Prerequisite: ChemS 160*. Generalizations of the periodic table and their relationship to classical and modern concepts of atomic and molecular structure. Inorganic stereochemistry including concepts of crystal chemistry, silicate chemistry, coordination theory, ligand field theory, catalysis, acid-base theory, reaction mechanisms, organometallic chemistry and a detailed consideration of selected groups of the periodic table.

ChemS 210. Materials Chemistry (3-0-3) *Prerequisite: ChemS 160*. This course will present fundamental concepts in materials chemistry. The main topics to be covered include structure and characterization, macroscopic properties and synthesis and processing.

ChemS 220. Organometallic Chemistry (3-0-3) Systematic consideration of modern aspects of organometallic chemistry including main group and transition metal complexes. The structure and binding in organometallic compounds is covered. Particular emphasis is placed on applications of homogenous organometallic catalysis in polymer synthesis, industrial processes and synthetic organic chemistry.

ChemS 230. Physical Chemistry of Macromolecules (2-0-2) *Prerequisite: ChemS 160 or equivalent.* Physical chemistry of macromolecules, including the theory for the experimental methods used for the study of macromolecular solutions.

ChemS 240. Organic Principles (3-0-3) Principles of chemical bonding, mechanisms of organic chemical reactions and stereochemistry. The important types of organic reactions are discussed. Basic principles are emphasized and relatively little attention is paid to the scope and synthetic applications of the reactions.

ChemS 250. Spectrochemical Methods of Analysis (3-0-3) *Prerequisite: ChemS 150 or equivalent*. Physical principles of instrumentation for spectrochemical analysis with emphasis on condensed matter and biological applications.

ChemS 260. Chemical Kinetics (3-0-3) A general course in chemical kinetics, useful for any branch of chemistry where reaction rates and mechanisms are important. Scope of subject matter: practical analysis of chemical reaction rates and mechanisms, theoretical concepts relating to gas and solution phase reactions.

ChemS 265. Quantum Chemistry (3-0-3) Constitutes, together with ChemS 270, a full course for students specializing in physical chemistry. Review of quantum mechanics from a postulational viewpoint; variational and matrix methods; time-independent and time-dependent perturbation theory; applications to molecular systems including potential energy surfaces and reaction pathways.

ChemS 270. Statistical Mechanics (3-0-3) Constitutes, together with ChemS 265, a full course for students specializing in physical chemistry. The foundation of equilibrium statistical mechanics and applications to problems of chemical interest. Included are discussions of imperfect gases and liquids, mixtures, solids, quantum statistics, surface chemistry and polymers.

ChemS 300. Biophysical Chemistry I (3-0-3) *Prerequisite: permission of the instructor.* This course is the first of the two-term biophysical chemistry series ChemS 300/325. The course offers an overview of protein, nucleic acid, lipid and carbohydrate structures.

ChemS 325. Biophysical Chemistry II (3-0-3) *Prerequisite: permission of the instructor.* This course is the second of the two-term biophysical chemistry series ChemS 300/325. The course offers an overview of protein, nucleic acid, lipid and carbohydrate structures.

ChemS 330. Laboratory in Macromolecular Chemistry (1-1-3) *Prerequisite: ChemS 230 or permission of the instructor.* Experimental methods for the study of macromolecular materials in solution and in bulk state.

ChemS 335. Organic Chemistry of Macromolecules (2-0-3) The preparation, reactions and properties of high-molecular-weight polymeric materials of both natural and synthetic origin.

ChemS 340. Application of Physical Methods to Organic Chemistry (3-0-3) Applications of infrared, ultraviolet, nuclear magnetic resonance spectroscopy, optical rotatory dispersion, mass spectrometry and other physical methods to the study and identification of the structure and reactions of organic compounds.

ChemS 345. Organic Mechanisms (2-0-2) Propose and write reasonable mechanisms for organic reactions, including complex multi-step processes.

ChemS 350. Molecular Modeling and Simulations (3-0-3) Familiarizes students with some of the most important computational methods in the molecular sciences. Includes lecture-type presentations of scientific background of methods and computational laboratory using common software packages.

ChemS 355. Nuclear Chemistry (3-0-3) The properties of the nucleus and a review of techniques for studying such properties. Radioactive decay processes, nuclear models, nuclear reactions and interactions of radiation with matter; applications of nuclear techniques to non-nuclear problems.

ChemS 360. Molecular Spectra and Structure (3-0-3) Review of atomic spectra; rotational, vibration-rotation and electronic spectra of diatomic and simple polyatomic molecules; deduction of molecular parameters from spectra.

ChemS 365. Separation Processes (3-0-3) *Prerequisite: ChemS 250 or permission of the instructor.* Requirements for analytical and preparational separations, pertinent phase rule considerations, theoretical plate concepts, efficiency calculations for multistage processes, nature of adsorption. Theory and practice of (a) precipitation and crystallization; (b) volatilization and distillation; and (c) extraction, partition and distribution processes, especially ion-exchange, liquid-liquid extraction and various types of adsorption and partition chromatography (gas, paper, thin-layer, etc.).

ChemS 370. Spectroscopy (3-0-3) *Prerequisite: ChemS 150 or equivalent.* Theory, practice and application of spectrochemical techniques for analysis and research with emphasis on emission and absorption spectroscopy in the principal regions of the electromagnetic spectrum.

ChemS 375. Electroanalytical Chemistry (3-0-3) Fundamentals of modern electroanalytical methods including potentiometry, ion-selective electrodes, gas sensors, voltammetry, amperometry, conductimetry, chemically modified electrodes, pulsed voltammetric techniques and biosensors. Instrumentation associated with these methods is also examined.

ChemS 380. Principles of Magnetic Resonance (2-0-2) *Prerequisite: ChemS 265 or permission of the instructor.* Classical and quantum mechanical treatments of magnetic resonance phenomena. Included will be discussions of spin systems, rotating fields, electron-nucleus interactions and relaxation phenomena. Experimental and theoretical aspects of nuclear magnetic resonance, electron spin resonance, 2-D NMR and the product operator formalism; chemical shifts, spin-spin coupling, hyperfine interactions, spin-lattice relaxation and other topics.

ChemS 400. Advanced Organic Chemistry (3-0-3) *Prerequisite: ChemS 240.* The scope and limitations of the more important synthetic reactions are discussed within the framework of multi-step organic synthesis.

ChemS 410. Advanced Inorganic Chemistry (3-0-3) *Prerequisite: ChemS 200 and ChemS 170 or equivalent.* The application of theoretical principles to the experimental observations of modern inorganic chemistry: ligand field and molecular orbital theory of complex ions, structural chemistry, magnetic properties, ESR, Mossbauer spectra, NQR.

ChemS 420. Mass Spectrometry (3-0-3) This course is focused on gaining a deep understanding of the physical principles of this mass spectrometry, including generation and measurement of high vacuum, sample introduction systems, ionization methods, ion optics, mass analysis, ion detection, electronics and data processing. Methods for tandem mass spectrometry (MS/MS) experiments are also discussed in detail, including collision-induced dissociation, surface-induced dissociation, photo dissociation and techniques involving radical ion chemistry, e.g., electron capture and transfer dissociation, as well a implementation of MS/MS on various mass analyzers.

ChemS 430. Principles of Molecular Symmetry and Solid State Chemistry (2-0-2) *Prerequisite: permission of the instructor.* The use of group theory in the discussion of molecular symmetry, crystal symmetry and the symmetry of operators and eigenfunctions. Discussion of lattices, space groups, selection rules and normal modes in crystals; motions and interactions of molecules in condensed phases; excitons in molecular crystals and aggregates.

ChemS 440. Special Topics in Inorganic Chemistry (2-0-2) *Prerequisite: ChemS 200.* The elements: main group elements, transition metals, organometallics.

ChemS 450. Special Topics in Organic Chemistry (2-0-2) *Prerequisite: ChemS 400.* Hetero-organic chemistry: open chain nitrogen compounds, organometallic compounds, heterocyclic compounds.

9. COMPUTER SCIENCE PROGRAM

The Computer Science program prepares students for success in a broad range of computing activities. This preparation emphasizes the scientific, mathematical and engineering-oriented aspects of computing necessary to contribute in information technology at multiple levels. The program in CS offers three tracks, each of which leads to a frontier of computing. The three track areas are:

- Theoretical Computer Science (Theory)
- Computer Systems (Systems)
- Artificial Intelligence (AI)

A student seeking a degree in Computer Science must specify one track area as a major. For the M.S. degree, course requirements include four designated Core courses, as well as a minimum of three Immersion courses and one Specialty course from the student's chosen major area. Additional elective coursework to meet the credit requirements for the degree gives students the flexibility to pursue further breadth and/or depth in their program. Each course carries 3 credit hours.

The M.S. degree requirement is 30 credits of courses (generally comprised of 10 courses). Typically, students will take 12 credits (4 courses) per semester in the program, completing the M.S. program in 3 semesters (1.5 years).

Students pursuing a Ph.D. must first satisfy the coursework requirements for the M.S. program, take at least 6 additional credits (for a minimum of 12 courses overall), pass qualifying examinations and pursue original research culminating in a doctoral dissertation. Ph.D. coursework in CS includes diversity requirements in applied and computational mathematics that connect the computer scientist to principal drivers of computer science from other disciplines. Completing the Ph.D. program generally takes 3 additional years beyond the completion of the M.S. program requirements. Further details on degree coursework requirements as well as Ph.D. program qualification and requirements are described in Section 4.

The courses required for all students in the CS program include:

- Artificial Intelligence (CS 221)
- Operating Systems and Systems Programming (CS 240)
- Compilers (CS 243)
- Algorithmic Paradigms (CS 261)

The Immersion courses in each CS track are as follows:

Theoretical Computer Science

- Combinatorial and Mathematical Programming (CS 208)
- Linear and Nonlinear Optimization (CS 211)
- Machine Learning (CS 229)
- Programming Languages (CS 242)
- Computer Graphics (CS 248)
- Information Networks (CS 337)

Computer Systems

- Digital Systems (CS 209)
- Programming Languages (CS 242)
- Computer Networks (CS 244)
- Databases (CS 245)
- Computer Graphics (CS 248)
- Computer Architecture and Organization (CS 282)

Artificial Intelligence

- Linear and Nonlinear Optimization (CS 211)
- Machine Learning (CS 229)
- Databases (CS 245)
- Numerical Optimization (CS 304)
- Computational Methods in Data Mining (CS 340)

The Specialty courses in the CS program are specified by individual faculty members and may vary from year to year.

COMPUTER SCIENCE PROGRAM COURSES

Note: CS courses listed below include cognates of some courses in the Applied Mathematics and Computational Science (AMCS) program.

CS 100. Vector Calculus for Engineers (3-0-3) (Same as AMCS 100.) Computation and visualization using MATLAB. Differential vector calculus: analytic geometry in space, functions of several variables, partial derivatives, gradient, unconstrained maxima and minima, Lagrange multipliers. Integral vector calculus: multiple integrals in Cartesian, cylindrical and spherical coordinates; line integrals; scalar potential; surface integrals; Green's, divergence and Stokes' theorems. Examples and applications drawn from various engineering fields.

CS 101. Programming Methodology and Abstractions (3-0-3) Computer programming and the use of abstractions. Software engineering principles of data abstraction and modularity. Object-oriented programming, fundamental data structures (such as stacks, queues, sets) and data-directed design. Recursion and recursive data structures (linked lists, trees, graphs). Introduction to basic time and space complexity analysis. The course teaches the mechanics of the C, C++ or Java language. This course is considered remedial training for students in the CS program and will not count toward any degree requirement.

CS 102. Ordinary Differential Equations for Engineers (3-0-3) (Same as AMCS 102.) *Prerequisite: CS 100.* Analytical and numerical methods for solving ordinary differential equations arising in engineering applications: solution of initial- and boundary-value problems, series solutions, Laplace transforms and non-linear equations; numerical methods for solving ordinary differential equations, accuracy of numerical methods, linear stability theory, finite differences. MATLAB programming as a tool kit for computations. Problems from various engineering fields.

CS 104. Linear Algebra and Partial Differential Equations for Engineers (3-0-3) (Same as AMCS 104.) *Prerequisite: CS 102.* Linear algebra: matrix operations, systems of algebraic equations, Gaussian elimination, undetermined and overdetermined systems, coupled systems of ordinary differential equations, eigensystem analysis and normal modes. Fourier series with applications, partial differential equations arising in science and engineering, analytical solutions of partial differential equations. Numerical methods for partial differential equations: iterative techniques, stability and convergence, time advancement, implicit methods, von Neumann stability analysis. Examples and applications from various engineering fields.

CS 106. Introduction to Probability and Statistics for Engineers (3-0-3) (Same as AMCS 106.) *Prerequisite: CS 100.* Probability: random variables, independence and conditional probability; discrete and continuous distributions, moments, distributions of several random variables. Topics in mathematical statistics: random sampling, point estimation, confidence intervals, hypothesis testing, non-parametric tests, regression and correlation analyses; applications in engineering, industrial manufacturing, medicine, biology and other fields.

CS 108. Introduction to Scientific Computing (3-0-3) *Prerequisite: CS 100.* (Same as AMCS 108.) This course covers numerical computation for mathematical, computational and physical sciences and engineering: numerical solution of systems of algebraic equations, least squares, quadrature, minimization of a function, banded matrices, nonlinear equations, numerical solution of ordinary and partial differential equations; truncation error, numerical stability for time-dependent problems, stiffness, boundary-value problems.

CS 154. Introduction to Automata and Complexity Theory (3-0-3) *Prerequisites: working knowledge of basic discrete mathematics (e.g., sets and functions) and proof techniques.* Regular sets: finite automata, regular expressions, equivalences among notations, methods of proving a language not to be regular. Context-free languages: grammars, pushdown automata, normal forms for grammars, proving languages non-context-free. Turing machines: equivalent forms, undecidability. Nondeterministic Turing machines: properties, the class NP, complete problems for NP, Cook's theorem, reducibilities among problems.

CS 157. Logic and Automated Reasoning (3-0-3) *Prerequisites: working knowledge of basic discrete mathematics (e.g., sets and functions) and proof techniques.* An elementary exposition from a computational point of view of propositional and predicate logic, axiomatic theories and theories with equality and induction. Interpretations, models, validity, proof, strategies and applications. Automated deduction: polarity, skolemization, unification, resolution, equality.

CS 161. Design and Analysis of Algorithms (3-0-3) *Prerequisites: solid computer programming skills (at least at the level of CS 101) and knowledge of probability (CS 106).* Efficient algorithms for sorting, searching and selection. Algorithm analysis: worst- and average-case analysis. Recurrences and asymptotics. Data structures: balanced trees, heaps, hash tables. Algorithm design techniques: divide-and-conquer, dynamic programming, greedy algorithms, amortized analysis. Algorithms for fundamental graph problems such as depth-first search, connected components, topological sort and shortest paths. Possible additional topics: network flow, string searching, parallel computation.

CS 200. Linear Algebra with Applications (3-0-3) (Same as AMCS 200.) *Prerequisite: CS 100.* Direct and iterative methods to solve linear systems of equations arising in engineering applications. The theory of linear algebra: basis, linear independence, column space, null space, rank; round-off errors, pivoting and ill-conditioned matrices; norms and condition numbers; projections and least squares; eigenvalues, eigenvectors and their computation; the canonical diagonal form; functions of a matrix; solution of systems of nonlinear equations arising in engineering applications.

CS 206. Introduction to Numerical Methods for Engineering (3-0-3) (Same as AMCS 206.) *Prerequisite: CS 200.* Numerical methods from a user's point of view. Lagrange interpolation, splines. Integration: trapezoid, Romberg, Gauss, adaptive quadrature; numerical solution of ordinary differential equations: explicit and implicit methods, multistep methods, Runge-Kutta and predictor-corrector methods, boundary-value problems, eigenvalue problems; systems of differential equations, stiffness. Emphasis is on analysis of numerical methods for accuracy, stability and convergence. Introduction to numerical solutions of partial differential equations; von Neumann stability analysis; alternating-direction implicit methods and nonlinear equations.

CS 208. Combinatorial and Mathematical Programming (3-0-3) (Same as AMCS 208.) Combinatorial and mathematical programming (integer and non-linear) techniques for optimization. Topics: linear program duality and LP solvers; integer programming; combinatorial optimization problems on networks including minimum spanning trees, shortest paths and network flows; matching and assignment problems; dynamic programming; linear approximations to convex programs; NP-completeness. Hands-on exercises.

CS 209. Digital Systems (3-0-3) *Prerequisites: facility with at least one programming language (at least at the level of CS 101) and logic.* The design of processor-based digital systems. Instruction sets, addressing modes, data types. Assembly language programming, low-level data structures, introduction to operating systems and compilers. Processor microarchitecture, microprogramming, pipelining. Memory systems and caches. Input/output, interrupts, buses and DMA. System design implementation alternatives, software/hardware tradeoffs. Labs involve the design of processor subsystems and processor-based embedded systems.

CS 211. Linear and Nonlinear Optimization (3-0-3) (Same as AMCS 211.) *Prerequisite: CS 200.* Optimization theory and modeling. The role of prices, duality, optimality conditions and algorithms in finding and recognizing solutions. Perspectives: problem formulation, analytical theory, computational methods and recent applications in engineering, finance and economics. Theories: finite dimensional derivatives, convexity, optimality, duality and sensitivity. Methods: simplex and interior-point, gradient, Newton and barrier.

CS 221. Artificial Intelligence (3-0-3) *Prerequisites: working knowledge of basic discrete mathematics (e.g., sets and functions) and proof techniques, programming ability (at least at the level of CS 101) and exposure to probability.* An introduction to the principles and practices of artificial intelligence. Topics include: search, constraint satisfaction, knowledge representation, probabilistic models, machine learning, neural networks, vision, robotics and natural language understanding.

CS 229. Machine Learning (3-0-3) *Prerequisites: linear algebra (comparable to CS 104) and basic probability and statistics (comparable to CS 106), CS 221.* Topics: statistical pattern recognition, linear and non-linear regression, non-parametric methods, exponential family, GLIMs, support vector machines, kernel methods, model/feature selection, learning theory, VC dimension, clustering, density estimation, EM, dimensionality reduction, ICA, PCA, reinforcement learning and adaptive control, Markov decision processes, approximate dynamic programming and policy search.

CS 240. Operating Systems and Systems Programming (3-0-3) *Prerequisite: solid computer programming skills (at least at the level of CS 101).* Operating systems design and implementation. Basic structure; synchronization and communication mechanisms; implementation of processes, process management, scheduling and protection; memory organization and management, including virtual memory; I/O device management, secondary storage and file systems.

CS 242. Programming Languages (3-0-3) *Prerequisites: programming experience with Lisp, C and an object-oriented programming language.* Central concepts in modern programming languages, impact on software development, language design trade-offs and implementation considerations. Functional, imperative and object-oriented paradigms. Formal semantic methods and program analysis. Modern type systems, higher-order functions and closures, exceptions and continuations. Modularity, object-oriented languages, and concurrency. Runtime support for language features, interoperability and security issues.

CS 243. Compilers (3-0-3) *Prerequisites: solid computer programming skills (at least at the level of CS 101), familiarity with formal languages (regular expressions and grammars).* Principles and practices for design and implementation of compilers and interpreters. Topics: lexical analysis, parsing theory, symbol tables, type systems, scope, semantic analysis, intermediate representations, run-time environments, code generation and basic program analysis and optimization. Students construct a compiler for a simple object-oriented language during course programming projects.

CS 244. Computer Networks (3-0-3) *Prerequisite: CS 240.* Packet switching, Internet architecture, routing, router architecture, flow control algorithms, retransmission algorithms, congestion control, TCP/IP, detecting and recovering from errors, switching, Ethernet (wired and wireless) and local area networks, physical layers. clocking and synchronization. Assignments introduce network programming, including sockets, designing a router and implementing a transport layer.

CS 245. Databases (3-0-3) *Prerequisites: working knowledge of basic discrete mathematics (e.g., sets, functions and relations) and programming skills (at least at the level of CS 101).* Database design and use of database management systems for applications. The relational model, relational algebra and SQL, the standard language for creating, querying and modifying relational and object-relational databases. XML data including the query languages XPath and XQuery. UML database design and relational design principles based on functional dependencies and normal forms. Other topics include indexes, views, transactions, authorization, integrity constraints and triggers. Advanced topics from data warehousing, data mining, Web data management, Datalog, data integration, data streams and continuous queries and data-intensive Web services.

CS 247. Human-Computer Interaction (3-0-3) *Prerequisite: computer programming skills (at least at the level of CS 101).* Usability and affordances, direct manipulation, systematic design methods, user conceptual models and interface metaphors, human cognitive and physical ergonomics, information and interactivity structures and design tools and environments.

CS 248. Computer Graphics (3-0-3) *Prerequisites: solid programming skills (at least at the level of CS 101) and linear algebra.* Input and display devices, scan conversion of geometric primitives, 2D and 3D geometric transformations, clipping and windowing, scene modeling and animation, algorithms for visible surface determination, local and global shading models, color and real-time rendering methods.

CS 261. Algorithmic Paradigms (3-0-3) *Prerequisite: CS 161.* Topics: algorithms for optimization problems such as matching, max-flow, min-cut and load balancing. Using linear programming, emphasis is on LP duality for design and analysis of approximation algorithms. Approximation algorithms for NP-complete problems such as Steiner trees, traveling salesman and scheduling problems. Randomized algorithms.

CS 282. Computer Architecture and Organization (3-0-3) *Prerequisite: CS 209.* Advanced topics in cache hierarchies, memory systems, storage and IO systems, interconnection networks and message-passing multiprocessor systems (clusters). Issues such as locality, coarse-grain parallelism, synchronization, overlapping communication with computation, hardware/software interfaces, performance/power trade-offs and reliability. Characteristics of modern processors that affect system architecture.

CS 304. Numerical Optimization (3-0-3) *Prerequisite: CS 200. Recommended: AMCS 171.* Solution of nonlinear equations. Optimality conditions for smooth optimization problems. Theory and algorithms to solve unconstrained optimization, linear programming, quadratic programming, global optimization, general linearly and nonlinearly constrained optimization problems. Programming project.

CS 308. Stochastic Methods in Engineering (3-0-3) (Same as AMCS 308.) *Prerequisite: CS 106.* Review of basic probability; Monte Carlo simulation; state space models and time series; parameter estimation, prediction and filtering; Markov chains and processes; stochastic control and stochastic differential equations. Examples from various engineering disciplines.

CS 337. Information Networks (3-0-3) (Same as AMCS 337.) *Prerequisite: basic probability and graph theory.* Network structure of the Internet and the Web. Modeling, scale-free graphs, small-world phenomenon. Algorithmic implications in searching and inter-domain routing, the effect of structure on performance. Game theoretic issues, routing games and network creation games. Security issues, vulnerability and robustness.

CS 340. Computational Methods in Data Mining (3-0-3) (Same as AMCS 340.) *Prerequisites: CS 106, CS 108.* Focus is on very-large-scale data mining. Topics include computational methods in supervised and unsupervised learning, association mining and collaborative filtering. Individual or group applications-oriented programming project. 1 unit without project; 3 units requires final project.

10. EARTH SCIENCE AND ENGINEERING PROGRAM

The program has two tracks:

- Fluid Earth Systems
- Solid Earth Systems

The Fluid Earth Systems track encompasses flow and transport processes both beneath and above the earth's surface, including subsurface, surface and atmospheric flows. Solid Earth Systems encompasses the areas of seismology, geophysics, geodynamics and geomechanics.

A student seeking a degree in ErSE must specify one track as a major, take a minimum of 3 courses at the 200 level or above in that track for the M.S. degree, and an additional 2 courses at the 300 level or above in that track for the Ph.D. degree. Each course carries 3 credit hours.

The M.S. degree requirement is 30 credit hours, and the Ph.D. requires a minimum of an additional 6 credit hours of course work and 24 hours of dissertation research. Typically, the duration of the M.S. program is 1.5 years, and the Ph.D. program is 3 years beyond that. More detailed information on degree requirements, including qualifying, candidacy, dissertation and final defense, are described in a separate document. Further details on degree coursework requirements as well as Ph.D. program qualification and requirements are described in Section 4.

The courses in each track are as follows:

Fluid Earth Systems
ErSE 200, ErSE 201, ErSE 202, ErSE 215, ErSE 220, ErSE 253
ErSE 301, ErSE 302, ErSE 312, ErSE 313, ErSE 318, ErSE 319, ErSE 320, ErSE 321, ErSE 322, ErSE 324, ErSE 410

Solid Earth Systems
ErSE 210, ErSE 211, ErSE 212, ErSE 215, ErSE 253, ErSE 260, ErSE 262
ErSE 311, ErSE 312, ErSE 313, ErSE 314, ErSE 320, ErSE 321, ErSE 322, ErSE 324, ErSE 410

Courses from other programs related to the Fluid Earth Systems track:
EnSE 221, EnSE 222, EnSE 223, EnSE 224, EnSE 304, EnSE 321, MarSEA 211, MarSEA 212, MarSEA 213, MarSEA 214, MarSEA 215, MarSEA 216, MarSEA 311, MarSEA 313, MarSEA 314, MarSEA 315

In addition to the above, a number of courses from Applied Mathematics and Computational Science, Computer Science and Mechanical Engineering may serve as appropriate electives for students in ErSE.

EARTH SCIENCE AND ENGINEERING PROGRAM COURSE DESCRIPTIONS

ErSE 120. Advanced Mathematics for ErSE Basic topics in real and complex analysis, ordinary and partial differential equations and other areas of applied mathematics with applications to fluid and solid earth systems.

ErSE 200. Petrophysics *Prerequisites: ME 260 and ErSE 120 or consent of instructor.* Measurement, interpretation and analysis of geological porous and permeable media. Geological and mathematical investigation of the pore-scale basis for flow and transport phenomena and petrophysical properties of sedimentary rocks. The macroscale equations governing the flow and advective-diffusive transport of fluids in porous media and their application to hydrological, petroleum and geosystems engineering problems. Treatment of uncertainty.

ErSE 201. Geophysical Fluid Dynamics I *Prerequisites: ME 250 and ErSE 120 or consent of instructor.* Topics include governing equations of mass and momentum conservation; wave kinematics, dispersion, group velocity; surface and internal gravity waves, shallow water theory; stratified fluids and normal mode analysis; waves in rotating fluids: Kelvin, Poincare and Rossby waves; the Rossby adjustment problem and conservation of potential vorticity; the quasi-geostrophic approximation; planetary waves and Charney-Drazin theory; barotropic and baroclinic instability theory.

ErSE 202. Flow in Porous Media *Prerequisites: ME 250, AMCS 108 or AMCS 206, and ErSE 120, or consent of instructor. Co-requisite: ErSE 200.* Derivation of mathematical models for porous media flow. Development and application of mass-conservative simulator models of single phase, miscible fluids in porous media. Solution of the pressure equation. Numerical methods for convection-diffusion equations.

ErSE 210. Seismology I *Prerequisites: ME 260 and ErSE 120 or consent of instructor.* Introductory and advanced concepts of seismic wave propagation. Vectors and tensors, Hooke's law, elastic coefficient tensors, effective media theories, Christoffel equation, group and phase velocities, boundary conditions, representation theorem, seismogram synthesis in layered media, asymptotic methods.

ErSE 211. Global Geophysics *Prerequisites: ME 260 and ErSE 120 or consent of instructor. Co-requisite: ErSE 210.* Earth and planets, early history, plate motions, magnetism and sea floor spreading, earthquakes and earth structure, gravity, geochronology, heat flow, mantle convection and earth's magnetic field.

ErSE 212. Geodynamics *Prerequisite: ME 260*. Plate tectonics and paleomagnetism. Global tectonics; rigid plate theory; heat flow, paleomagnetic data interpretation, including field methods; marine geophysics. Basin subsidence. Modeling of basin development, including gravity, flexure, subsidence, rheology and back-stripping methods. Geodesy. Gravity field of the whole earth, tides, rotational variation, space geodetic methods for crustal strain studies.

ErSE 215. Petrology Composition and texture of igneous rocks. Sedimentary processes related to the dynamics of bed forms and the origin of sedimentary structures. Deformation processes and resultant textures and fabrics and conditions required to produce such deformation.

ErSE 220. Geochemistry *Prerequisites: AMCS 108 or AMCS 206, and ErSE 200.* Fundamentals of subsurface chemistry, including mineralization, dissolution, microbiology and biochemistry, and radionuclide decay as applied to environmental pollution and treatment processes and petroleum recovery. Numerical solution of reaction and advection-diffusion-reaction systems.

ErSE 253. Geostatistics *Prerequisites: AMCS 106 and ErSE 200.* Stochastic methods, including variogram and covariance analysis and modeling, spatial interpolation (kriging), data integration, Monte-Carlo and Markov-Bayes stochastic simulation, uncertainty assessment, multipoint geostatistics.

ErSE 260. Seismic Imaging *Prerequisites: AMCS 108 or AMCS 206, and ErSE 210.* Geometrical seismics: travel times and amplitudes, rays and wavefronts; eikonal and transport equations. Numerical wave extrapolation: Kirchhoff and wave-equation migration, reverse-time migration, imaging conditions, near-surface corrections and datuming. Time migration and data mapping: prestack time migration, offset and shot continuation, normal and dip moveout, elimination of multiple reflections. Principles of velocity estimation and model building: migration velocity analysis, seismic tomography.

ErSE 262. Quantitative Seismic Interpretation *Prerequisites: AMCS 108 or AMCS 206, and ErSE 210.* Basic rock physics, seismic attributes, pre- and post-stack inversion, multi-attributes, neural networks, data integration.

ErSE 301. Multiphase Flows in Porous Media *Prerequisite: ErSE 202*. Thermodynamics of pressure, volume, temperature and composition relationships in water, oil or nonaqueous phase liquids and gas mixtures. Modeling compositional and thermal fluids, including streamline flow, fractional flow and both immiscible and miscible flow.

ErSE 302. Geophysical Fluid Dynamics II *Prerequisites: AMCS 108 or AMCS 206, and ErSE 201.* Basic principles of conservation laws: weak solutions, jump conditions, characteristics, shocks and rarefactions, entropy conditions. Numerical solution of linear and nonlinear conservation laws arising in geophysical fluid dynamics: shock-capturing, total-variation-diminishing schemes, flux and slope limiting, stabilized finite element methods. Extensions to nonlinear systems and convection-diffusion equations.

ErSE 311. Seismology II *Prerequisites: AMCS 108 or AMCS 206, and ErSE 210.* Fourier and Radon transforms, reflection coefficient, reflectivity computation, finite differences, finite elements, rays and beams, eikonal equation, imaging.

ErSE 312. Exploration Geophysics *Prerequisites: ErSE 210 and ErSE 120 or consent of instructor.* Seismic, gravity, magnetic, electrical and electromagnetic methods of exploration for petroleum and minerals.

ErSE 313. Geomechanics *Prerequisites: ME250, ME260, AMCS108 or AMCS206, ErSE 120.* Mechanics of porous media from a computational standpoint. Balance laws for multiphase continua, with and without inertial effects. Finite element implementation.

ErSE 314. Tectonics *Prerequisite: ErSE 215.* Regional structural features in the earth's crust and their origins, complex and controversial structures, plate tectonics.

ErSE 318. Hydroclimatology *Prerequisite: ErSE 201.* Topics in global and regional-scale hydroclimatic processes, including atmospheric dynamics and thermodynamics, the atmospheric boundary layer and land-surface processes, climate dynamics of the global water cycle, occurrence of flood-producing rainfall and droughts, teleconnections associated with climate anomalies and key global change issues explored using computer models.

ErSE 319. Physical Climatology *Prerequisite: ErSE 201.* Investigates the nature of earth's climate and examines the physical processes that maintain the climate system. Topics include the energy balance, the hydrological cycle, general atmosphere circulation and how they all interact and vary at various spatial and temporal scales. Discusses human-induced modifications to the climate system, such as urbanization, anthropogenic global warning, desertification and tropical deforestation.

ErSE 320. Inverse Problems *Prerequisite: completed M.S. requirements of either Fluid Earth Systems or Solid Earth Systems tracks.* Basic statistics, classical inverse theory, numerical optimization, regularization, global optimization, statistical inverse theory and uncertainty estimation.

ErSE 321. Multiscale Methods for Heterogeneous Media *Prerequisite: completed M.S. requirements of either Fluid Earth Systems or Solid Earth Systems tracks.* Theoretical and numerical multiscale analysis for porous and heterogeneous media. Topics include homogenization, dual-porosity models, multiscale mortar finite elements and domain decomposition and variational multiscale methods.

ErSE 322. Advanced Theory of Finite Elements *Prerequisite: ME 365.* Advanced topics in the theory and application of finite element methods to fluid and solid earth systems problems.

ErSE 324. Parallel Scientific Computing in Earth Sciences *Prerequisites: AMCS108 or AMCS206, ErSE 120*. Introduction to the basics of modern parallel computing: parallel architectures, message passing, data and domain decomposition, parallel libraries, programming languages, data management and visualization and parallel numerical algorithms. Applications to scientific computing problems in earth sciences and engineering.

ErSE 410. Advanced Algorithms for Scientific Computation in Earth Sciences *Prerequisite: completed M.S. requirements of either Fluid Earth Systems or Solid Earth Systems tracks.* Topics may vary from semester to semester depending on instructor. Topics may include advanced linear and nonlinear solvers for anisotropic/heterogeneous PDEs, fast multipole methods, level set techniques, numerical solution of Eikonal equations and numerical methods for geomechanics, poroelasticity and plasticity.

11. ELECTRICAL ENGINEERING PROGRAM

The program has three major tracks, each consisting of six or more courses in each of two closely related areas. The three tracks together cover the most important areas in modern-day electrical engineering, and should equip a student for a successful and productive career in these fields.

The three tracks are:

- Solid-State Electronics: a) Circuits and Microsystems and b) Solid-State Devices
- Electromagnetics and Optics
- Communications and Signal Processing

A student seeking a degree in electrical engineering must specify one track as a major, take a minimum of three courses in that track for the M.S. degree, and an additional two courses in that track at the 300 level or above for the Ph.D. degree. As seen above, each track encompasses two areas. A student may wish to focus on one of these areas, taking most courses there, but this is not required. Each course carries 3 credit hours.

The M.S. degree requirement is 30 credit hours, and the Ph.D. requires a minimum of an additional 6 credit hours of course work and 24 hours of dissertation research. Typically, the duration of the M.S. program is 1.5 years, and the Ph.D. program is 3 years beyond that. More detailed information on degree requirements, including qualifying, candidacy, dissertation and final defense, are described in Section 4.

The courses in each track are as follows:

<u>Circuits and Microsystems</u>
EE 201, EE 202, EE 203, EE 204, EE 205
EE 301, EE 302, EE 303, EE 304

<u>Solid-State Devices</u>
EE 203, EE 204, EE 206, EE 207, EE 208
EE 305, EE 306. EE 307

<u>Electromagnetics</u>
EE 207, EE 221, EE 222, EE 223
EE 321, EE 322

<u>Optics</u>
EE 231, EE232, EE 233
EE 331, EE 332, EE 333, EE 334

<u>Communications</u>
EE 241, EE 242, EE 243
EE 341, EE 342, EE 343

Signal Processing
EE 241, EE 251, EE 252, EE 253
EE 351, EE 352, EE 353

ELECTRICAL ENGINEERING PROGRAM COURSE DESCRIPTIONS

EE 201. VLSI Design (3-0-3) Design techniques for rapid implementations of very-large-scale integrated (VLSI) circuits, MOS technology and logic. Structured design. Design rules, layout procedures. Design aids: layout, design rule checking, logic and circuit simulation. Timing. Testability. Architectures for VLSI. Projects to develop and lay out circuits.

EE 202. Monolithic Amplifier Circuits (3-0-3) Analysis and design of BJT and MOS multi-transistor amplifiers. Feedback theory and application to feedback amplifiers. Stability considerations, pole-zero cancellation, root locus techniques in feedback amplifiers. Detailed analysis and design of BJT and MOS integrated operational amplifiers. Lectures and laboratory.

EE 203. Solid-State Device Laboratory (1-2-3) Semiconductor material and device fabrication and evaluation: diodes, bipolar and field-effect transistors, passive components. Semiconductor processing techniques: oxidation, diffusion, deposition, etching, photolithography. Lecture and laboratory. Projects to design and simulate device fabrication sequence.

EE 204. Integrated Microsystems Laboratory (1-2-3) Development of a complete integrated microsystem, from functional definition to final test. MEMS-based transducer design and electrical, mechanical and thermal limits. Design of MOS interface circuits. MEMS and MOS chip fabrication. Mask making, pattern transfer, oxidation, ion implantation and metallization. Packaging and testing challenges. Students work in interdisciplinary teams.

EE 205. Introduction to MEMS (3-0-3) Micro electro mechanical systems (MEMS), devices and technologies. Micro-machining and microfabrication techniques, including planar thin-film processing, silicon etching, wafer bonding, photolithography, deposition and etching. Transduction mechanisms and modeling in different energy domains. Analysis of micromachined capacitive, piezoresistive and thermal sensors/actuators and applications. Computer-aided design for MEMS layout, fabrication and analysis.

EE 206. Physical Principles Underlying Smart Devices (3-0-3) Structural properties of materials. Basic quantum mechanics of electrons in solids. Band theory and trap states. Charge transport, band conduction and hopping conduction. Optical properties of materials. Piezoelectric and ferro-electric phenomena. Magnetic effects in materials. Physical phenomena will be related transistors, light emitters, sensor and memory devices.

EE 207. Microwave Circuits (3-0-3) Transmission-line theory, microstrip and coplanar lines, S-parameters, signal-flow graphs, matching networks, directional couplers, low-pass and band-pass filters, diode detectors. Design, fabrication and measurements (1–10GHz) of microwave-integrated circuits using CAD tools and network analyzers.

EE 208. Semiconductor Optoelectronic Devices (3-0-3) Materials for optoelectronics, optical processes in semiconductors, absorption and radiation, transition rates and carrier lifetime. Principles of LEDs, lasers, photodetectors, modulators and solar cells. Optoelectronic integrated circuits. Designs, demonstrations and projects related to optoelectronic device phenomena.

EE 221. Electromagnetic Theory (3-0-3) Maxwell's equations, constitutive relations and boundary conditions. Potentials and the representation of electromagnetic fields. Uniqueness, duality, equivalence, reciprocity and Babinet's theorems. Plane, cylindrical and spherical waves. Waveguides and elementary antennas. The limiting case of electro- and magneto-statics.

EE 222. Numerical Methods in Electromagnetics (3-0-3) Introduction to numerical methods in electromagnetics including finite difference, finite element and integral equation methods for static, harmonic and time-dependent fields; use of commercial software for analysis and design purposes; applications to open and shielded transmission lines, antennas, cavity resonances and scattering.

EE 223. Antenna Theory and Design (3-0-3) Theory of transmitting and receiving antennas. Reciprocity. Wire antennas: dipoles, loops and traveling-wave antennas. Analysis and synthesis of linear arrays. Phased arrays. Input impedance and method of moments. Mutual impedance. Aperture antennas: slot, Babinet's principle. Microstrip antennas. Horns, reflector and lens antennas.

EE 231. Principles of Optics (3-0-3) Basic principles of optics: light sources and propagation of light; geometrical optics, lenses and imaging; ray tracing and lens aberrations; interference of light waves, coherent and incoherent light beams; Fresnel and Fraunhofer diffraction. Overview of modern optics with laboratory demonstrations.

EE 232. Applied Quantum Mechanics (3-0-3) Introduction to nonrelativistic quantum mechanics. Summary of classical mechanics, postulates of quantum mechanics and operator formalism, stationary state problems (including quantum wells, harmonic oscillator, angular momentum theory and spin, atoms and molecules, band theory in solids), time evolution, approximation methods for time-independent and time-dependent interactions including electromagnetic interactions, scattering.

EE 233. Photonics (3-0-3) *Prerequisite: EE 231.* Introduction to photonics, lasers and fiber optics. Topics include mirrors, interferometers, modulators and propagation in waveguides and fibers; photons in semiconductors, including semiconductor laser, detectors and noise effects, with applications to fiber lightwave systems, high-power lasers and display technologies.

EE 241. Probability and Random Processes (3-0-3) Introduction to probability and random processes. Topics include probability axioms, sigma algebras, random vectors, expectation, probability distributions and densities, Poisson and Wiener processes, stationary processes, autocorrelation, spectral density, effects of filtering, linear least-squares estimation and convergence of random sequences.

EE 242. Digital Communication and Coding (3-0-3) Digital transmission of information across discrete and analog channels. Sampling; quantization; noiseless source codes for data compression: Huffman's algorithm and entropy; block and convolutional channel codes for error correction; channel capacity; digital modulation methods: PSK, MSK, FSK, QAM; matched filter receivers. Performance analysis: power, bandwidth, data rate and error probability.

EE 243. Communication Networks (3-0-3) *Prerequisite: preceded or accompanied by EE 241.* System architectures. Data link control: error correction, protocol analysis, framing. Message delay: Markov processes, queuing, delays in statistical multiplexing, multiple users with reservations, limited service, priorities. Network delay: Kleinrock independence, reversibility, traffic flows, throughput analysis, Jackson networks. Multiple access networks: ALOHA and splitting protocols, carrier sensing, multi-access reservations.

EE 251. Digital Signal Processing and Analysis (3-0-3) Introduction to digital signal processing of continuous and discrete signals. The family of Fourier transforms including the discrete Fourier transform (DFT). Development of the fast Fourier transform (FFT). Signal sampling and reconstruction. Design and analysis of digital filters. Correlation and spectral estimation.

EE 252. Estimation, Filtering and Detection (3-0-3) *Prerequisite: EE 241.* Principles of estimation, linear filtering and detection. Estimation: linear and nonlinear minimum mean squared error estimation and other strategies. Linear filtering: Wiener and Kalman filtering. Detection: simple, composite, binary and multiple hypotheses. Neyman-Pearson and Bayesian approaches.

EE 253. Wavelets and Time-Frequency Distribution (3-0-3) *Prerequisite: EE 251.* Review of DTFT and digital filtering. Multirate filtering. Filter banks and sub-band decomposition of signals. Multiresolution subspaces. Wavelet scaling and basis functions and their design: Haar, Littlewood-Paley, Daubechies, Battle-Lemarie. Denoising and compression applications. Spectrogram, Wigner-Ville, Cohen's class of time-frequency distributions and their applications.

EE 301. Integrated Analog/Digital Interface Circuits (3-0-3) *Prerequisite: EE 201.* This course covers most of the well-known analog-to-digital conversion schemes. These include the flash, folding, multi-step and pipeline Nyquist rate, architectures. Oversampling converters are also discussed. Practical design work is a significant part of this course. Students design and model complete converters.

EE 302. Integrated Circuits (3-0-3) *Prerequisites: EE 201 and EE 202.* Integrated circuit fabrication overview, relationships between processing choices and device performance characteristics. Long-channel device I-V review, short-channel MOSFET I-V characteristics including velocity saturation, mobility degradation, hot carriers, gate depletion. MOS device scaling strategies, silicon-on-insulator, lightly doped drain structures, on-chip interconnect parasitics and performance. Major CMOS scaling challenges. Process and circuit simulation.

EE 303. Advanced MEMS Devices and Technologies (3-0-3) *Prerequisite: EE 205.* Advanced micro electro mechanical systems (MEMS) devices and technologies. Transduction techniques, including piezoelectric, electrothermal and resonant techniques. Chemical, gas and biological sensors; microfluidic and biomedical devices. Micromachining technologies such as laser machining and microdrilling, EDM, materials such as SiC and diamond. Sensor and actuator analysis and design through CAD.

EE 304. Integrated Microsystems (3-0-3) *Prerequisite: EE 205.* Review of interface electronics for sense and drive and their influence on device performance, interface standards, MEMS and circuit noise sources, packaging and assembly techniques, testing and calibration approaches and communication in integrated microsystems. Applications, including RF MEMS, optical MEMS, bioMEMS and microfluidics. Design project using CAD and report preparation.

EE 305. Electronic and Optical Properties of Semiconductors (3-0-3) *Prerequisite: EE 206.* The course discusses in detail the theory behind important semiconductor-based experiments such as Hall effect and Hall mobility measurement, velocity-field measurement, photoluminescence, gain, pump-probe studies, pressure and strain-dependent studies. Theory will cover: Band structure in quantum wells; effect of strain on band structure; transport theory; Monte Carlo methods for high field transport; excitons, optical absorption, luminescence and gain.

EE 306. High-Speed Transistors (3-0-3) *Prerequisite: EE 207.* Detailed theory of high-speed digital and high-frequency analog transistors. Carrier injection and control mechanisms. Limits to miniaturization of conventional transistor concepts. Novel submicron transistors including MESFET, heterojunction and quasi-ballistic transistor concepts.

EE 307. Semiconductor Lasers and LEDs (3-0-3) *Prerequisite: EE 208.* Optical processes in semiconductors, spontaneous emission, absorption gain, stimulated emission. Principles of light-emitting diodes, including transient effects, spectral and spatial radiation fields. Principles of semiconducting lasers, gain-current relationships, radiation fields, optical confinement and transient effects.

EE 321. Microwave Measurements Laboratory (3-0-3) *Prerequisites: EE 207 and 221.* Advanced topics in microwave measurements: power spectrum and noise measurement, introduction to state-of-the-art microwave test equipment, methods for measuring the dielectric constant of materials, polarimetric radar cross section measurements, near-field antenna pattern measurements, electromagnetic emission measurement (EM compatibility). Followed by a project that will include design, analysis, and construction of a microwave subsystem.

EE 322. Active Remote Sensing (3-0-3) *Prerequisites: EE 207 and 221.* Radar equation, noise statistics, resolution techniques, calibration. Space and ground propagation, synthetic aperture radar, scatterometers, scattering models, surface and volume scattering. Land and oceanographic applications.

EE 331. Classical Optics (3-0-3) *Prerequisite: EE 231.* Theory of electromagnetic, physical and geometrical optics. Classical theory of dispersion. Linear response, Kramers-Kronig relations and pulse propagation. Light scattering. Geometrical optics and propagation in inhomogeneous media. Dielectric waveguides. Interferometry and theory of coherence. Diffraction, Fresnel and Fraunhofer. Gaussian beams and the ABCD law.

EE 332. Optical Waves in Crystals (3-0-3) *Prerequisite: 233.* Propagation of laser beams: Gaussian wave optics and the ABCD law. Manipulation of light by electrical, acoustical waves; crystal properties and the dielectric tensor; electro-optic, acousto-optic effects and devices. Introduction to nonlinear optics; harmonic generation, optical rectification, four-wave mixing, self-focusing and self-phase modulation.

EE 333. Lasers (3-0-3) *Prerequisites: EE 331 and EE 332.* Complete study of laser operation: the atom-field interaction; homogeneous and inhomogeneous broadening mechanisms; atomic rate equations; gain and saturation; laser oscillation; laser resonators, modes and cavity equations; cavity modes; laser dynamics, Q-switching and modelocking. Special topics such as femto-seconds lasers and ultra-high-power lasers.

EE 334. Nonlinear Optics (3-0-3) *Prerequisites: EE 331 and EE 332.* Formalism of wave propagation in nonlinear media, susceptibility tensor, second harmonic generation and three-wave mixing, phase matching, third-order nonlinearities and four-wave mixing processes, stimulated Raman and Brillouin scattering. Special topics: nonlinear optics in fibers, including solitons and self-phase modulation.

EE 341. Information Theory (3-0-3) *Prerequisite: EE 241.* The concepts of source, channel, rate of transmission of information. Entropy and mutual information. The noiseless coding theorem. Noisy channels, the coding theorem for finite state zero memory channels. Channel capacity. Error bounds. Parity check codes. Source encoding.

EE 342. Channel Coding Theory (3-0-3) *Prerequisite: EE 241.* The theory of channel coding for reliable communication and computer memories. Error-correcting codes; linear, cyclic and convolutional codes; encoding and decoding algorithms; performance evaluation of codes on a variety of channels.

EE 343. Digital Communication Theory (3-0-3) *Prerequisites: EE 241, EE 242.* Theory of digital modulation and coding. Optimum receivers in Gaussian noise. Signal space and decision theory. Signal design. Bandwidth and dimensionality. Fundamental limits in coding and modulation. Capacity and cutoff rate. Block, convolutional and trellis coding. Continuous phase modulation. Filtered channels and intersymbol interference. Equalization. Spread-spectrum. Fading channels. Current topics.

EE 351. Advanced Signal Processing (3-0-3) *Prerequisites: EE 241, EE 251.* Estimators of second-order properties of random processes: nonparametric and model-based techniques of spectral estimation, characterization of output statistics for nonlinear systems, time-frequency representations. Performance evaluation using asymptotic techniques and Monte Carlo simulation. Applications include speech processing, signal extrapolation, multidimensional spectral estimation and beam forming.

EE 352. Image Processing (3-0-3) *Prerequisites: EE 241, EE 251.* Theory and application of digital image processing. Random field models of images. Sampling, quantization, image compression, enhancement, restoration, segmentation, shape description, reconstruction of pictures from their projections, pattern recognition. Applications include biomedical images, time-varying imagery, robotics and optics.

EE 353. Adaptive Signal Processing (3-0-3) *Prerequisites: EE 241, EE 251.* Theory and applications of adaptive filtering in systems and signal processing. Iterative methods of optimization and their convergence properties: transversal filters; LMS (gradient) algorithms. Adaptive Kalman filtering and least-squares algorithms. Specialized structures for implementation (e.g., least-squares lattice filters, systolic arrays). Applications to detection, noise canceling, speech processing and beam forming.

12. ENVIRONMENTAL SCIENCE AND ENGINEERING PROGRAM

Students entering the program take a set of Core courses and then take Specialty courses from one of four major tracks. The remaining courses are technical electives. The four tracks together cover the most important areas in modern-day Environmental Science and Engineering, and the Core plus Specialty courses and Electives should equip a student for a successful and productive career in these fields.

The four tracks are:

- Air and Water Quality
- Environmental Fluid Mechanics and Hydrology
- Environmental Chemistry and Microbiology
- Processes in Environmental Biotechnology

A student seeking a degree in Environmental Science and Engineering must, in addition to the Core courses, specify one track as a major, take a minimum of 2 courses in that track for the M.S. degree, and an additional 2 courses in that track at the 300-level or above for the Ph.D. degree. Each course carries 3 credit hours.

The M.S. degree requirement is 30 credit hours of coursework and the Ph.D. requires a minimum of an additional 6 credit hours of coursework and 24 credit hours of dissertation research. Typically, the duration of the M.S. program is 1.5 years, and the Ph.D. is 3 years beyond that. More detailed information on degree requirements, including qualifying, candidacy, dissertation and final defense, are described in Section 4.

The courses in the Core and in each track are as follows:

Core Courses
EnSE 201, EnSE 202, EnSE 203, EnSE 204, EnSE 205

Air and Water Quality
EnSE 211, EnSE 221, CBE 235
EnSE 302, EnSE 303, EnSE 304, EnSE 305, EnSE 312, EnSE 341, EnSE 342

Environmental Chemistry and Microbiology
EnSE 211, EnSE 213, CBE 235, B204, MarSE 226
EnSE 311, EnSE 312, EnSE 341, EnSE 342

Environmental Fluid Mechanics and Hydrology
EnSE 221, EnSE 222, EnSE 223, ErSE 201, ErSE 202, MarSE 212,
EnSE 304, EnSE 312, EnSE 321, ErSE 301, ErSE 302, MarSE 311, MarSE 314

Processes in Environmental Biotechnology
CBE 235, CBE 236, CBE 238, B204
EnsE 305, EnSE 311, EnSE 331, EnSE 341, EnSE 342, EnSE 350

ENVIRONMENTAL SCIENCE AND ENGINEERING PROGRAM COURSE DESCRIPTIONS

EnSE 201. Air and Water Quality (3-0-3) Introduction to outdoor and indoor air quality, measurement systems, fate of contaminants, air pollution control systems, gas and particle transport on multiple scales. Introduction to water quality, effluent, chemical elements, salinity. Physical, chemical and biological treatment processes for drinking, industrial and waste water.

EnSE 202. Environmental Chemistry (2-1-3) Chemistry of processes and behavior in air and aquatic systems. Acid-base and redox chemistry, carbonate system, precipitation. Chemical thermodynamics including quantitative assessment of chemical composition and fate of contaminants using equilibrium calculations.

EnSE 203. Environmental Microbiology (2-1-3) Fundamentals of microbiology for the environment, physiology, microbial metabolism, basics of genetics, microbial growth processes, introduction to molecular biology. Illustrations from microbiology and pollutants, microbiology and disease, microbiology of bioremediation, wastewater treatment, microbial fuel cells.

EnSE 204. Environmental Transport Processes (3-0-3) Movement and fate of chemicals and contaminants in air, water and soil. Mass balance and transfer, hydrodynamic transport, environmental sources and sinks.

EnSE 205. Principles of Environmental Sustainability (3-0-3) Fundamental aspects of sustainability, energy cycles and accounting. Carbon cycle, emissions and sequestration. Concepts of green design. Life-cycle analysis.

EnSE 211. Atmospheric Chemistry (3-0-3) Chemistry of atmospheric constituents, photochemistry and oxidation, chemistry of airborne pollutants.

EnSE 213. Environmental Organic Chemistry (3-0-3) Behavior and fate of organic compounds in the environment. Chemical properties, mechanisms, kinetics and reaction products in air, water and soils; photochemical and biochemical transformation reactions.

EnSE 221. Environmental Fluid Mechanics (3-0-3) Principles of fluid flow in natural systems including the atmosphere, rivers, lakes and oceans, and engineered systems such as in wastewater treatment. Roles of density variation and stratification, diffusion and turbulence.

EnSE 222. Surface Hydrology (3-0-3) Fundamentals of surface hydrology, the hydrologic cycle, hydrologic processes.

EnSE 223. Groundwater Hydrology (3-0-3) Groundwater hydrology, subsurface flow, geological considerations, aquifers and wells.

EnSE 302. Atmospheric Transport (3-0-3) *Prerequisites: EnSE 201, EnSE 204*. Contaminant transport in the atmosphere, mathematical models of pollutant dispersal, plumes, meteorology and climate change.

EnSE 303. Climate Change (3-0-3) *Prerequisite: EnSE 204*. Fundamentals of global climate change, inputs and assumptions in climate change models, modeling and simulation of the carbon cycle and CO_2 sequestration.

EnSE 304. Water Resource Engineering (3-0-3) *Prerequisite: EnSE 201*. Planning and management of water resources. Water supply, flood control, irrigation, mathematical modeling and optimization techniques.

EnSE 305. Air Quality Control Processes (3-0-3) *Prerequisite: EnSE 201.* Indoor and outdoor air quality control processes. Theory and practice of air pollution control. Sources, transport, fate, impacts, characteristics and control of air contaminants; design of control technologies for particulate, gaseous and VOC emissions.

EnSE 311. Molecular Biology and Microbial Ecology (2-1-3) *Prerequisites: EnSE 202, EnSE 203*. Principles of molecular biology in environmental science and engineering. Research methods, engineering tools. Principles of microbiological systems, genomics, microbial evolution, microbial diversity, the biogeochemical cycle.

EnSE 312. Advanced Aquatic and Soil Chemistry (3-0-3) *Prerequisite: EnSE 202.* Biogeochemistry, colloids, soil and gas or liquid interfaces, oxidation-reduction reactions and adsorption processes. Chemistry and properties of soil and soil processes.

EnSE 321. Numerical Modeling of Environmental Flows (3-0-3) *Prerequisite: EnSE 204.* Advanced numerical methods for environmental transport processes, multi-scale and multi-physics issues.

EnSE 331. Advanced Topics in Sustainability (3-0-3) *Prerequisite: EnSE 205*. Topic 1: Assessment of Energy and Resource Needs**.** Topic 2: Materials, Environment and Sustainability**.** Topic 3: Sustainable Engineering Systems.

EnSE 341. Processes in Environmental Biotechnology (3-0-3) *Prerequisite: EnSE 311.* Principles of molecular biology and microbiology applied to the design and operation of engineered environmental systems: treatment of wastewater, bioremediation, energy conversion.

EnSE 342. Physical/Chemical Treatment Processes (3-0-3) *Prerequisite: EnSE 201.* Water-treatment processes, membranes, advanced oxidation, principles and techniques of water desalination.

EnSE 350. Hazardous Waste Management (3-0-3) *Prerequisites: EnSE 201, EnSE 204.* Legal and technological approaches to control and management of hazardous wastes and contaminated sites to protect human health and the environment: fate and transport of contaminants; physical, chemical and biological treatment; environmental monitoring systems; medical waste and treatment options; toxicology; storage tanks; landfills.

13. MARINE SCIENCE AND ENGINEERING PROGRAM

Introduction and Basic Philosophy of the Degree

Science of the ocean is maturing with increasing focus on applications and problem solving. Marine science issues of societal relevance include the fate of global fisheries, the ocean's role in climate change, carbon dioxide sequestration in the ocean and impact of ocean acidification, to name just a few. Graduates of the KAUST Marine Science and Engineering (MarSE) program should be well placed to contribute toward local and global solutions in these and other marine science fields.

This MarSE curriculum is designed to meet three objectives: (1) provide introductory courses for KAUST students enrolled in the Environmental Science and Engineering Program who desire a background in MarSE topics, (2) provide courses for MarSE M.S. degree students and (3) provide advanced courses for MarSE Ph.D. degree students.

Marine science is interdisciplinary by nature, and marine science degree programs should allow considerable flexibility in the detailed choice of courses for M.S. and Ph.D. students. Course selection as well as comprehensive and qualifying exams should be tailored to an individual student's academic and research interests. It is expected that marine science students will include a significant number of courses taught in other science departments (e.g., genomics, as part of their M.S. or Ph.D. program of studies in Marine Science and Engineering).

The focus of the MarSE program is on the Red Sea as a model system for training graduate students and postdoctoral fellows in marine science and technology: as well as applications of marine science and technology to environmental and marine resource management.

This draft curriculum includes some of the components of an ocean engineering degree, but is not by itself a comprehensive program in ocean engineering. For example, we believe that marine structures could be best handled in Mechanical Engineering (ME). Similarly, we have not included ocean geophysics and seismology, as that is likely to be included in the ErSE curriculum.

Courses are organized by MarSE themes. Three introductory courses are required of all MarSE students, unless a comparable background can be demonstrated, but all other coursework is determined by the students and their advisors. The M.S. degree requirement is 30 credit hours, including 6 credit hours for M.S. thesis research, and the Ph.D. requires a minimum of an additional 12 hours of course work and 24 hours of dissertation research (total of 36 hours course work and 30 hours research). Typically, the duration of the M.S. degree is 1.5 to 2.0 years, and the Ph.D. degree is 3 years beyond that. More detailed information on degree requirements including qualifying, candidacy, dissertation and final defense are described in Section 4.

MarSE Courses

Courses are organized by MarSE themes plus two seminars that are common to all themes. Three introductory courses (MarSE 201, 202 and 203) are required unless a comparable background can be demonstrated. Core courses provide fundamental knowledge in the sub-disciplines of marine science and engineering and should generally be taken before other courses within one of the thematic areas.

1) The Marine Environment
2) Marine Life
3) Ocean Engineering
4) Management and Conservation of Marine Resources
5) Seminars

Courses are numbered and labeled as follows: MarSE XYZ, where X is the level of the course (with a 2 denoting first-year graduate level; 3 is intended for advanced (second-year and beyond) graduate students). Y is the theme (as above), and Z is the course number. Thus, MarSE 211 is a first-year graduate level course in the theme Marine Physical and Chemical Environment.

The courses shown here are those that are somewhat specific to marine science and ocean engineering. A KAUST MarSE graduate student will be expected to take courses outside of this list, including applied mathematics, basic chemistry, basic fluid mechanics, etc., that will be found in lists other than MarSE. Where we know of a likely overlap with courses in another curriculum, we have so indicated in parentheses in the list below.

A well-rounded curriculum will include seminar courses that expose the students (and staff) to the classic and modern literature in a field of study and that allow students an opportunity to learn presentation skills. In the Fall semester, first- and second-year MarSE students should participate in the MarSE 251 seminar, “Classic Papers in Oceanography,” and in the Spring semester MarSE 351, “Red Sea Oceanography.” In these seminar courses, students will have the opportunity to read, present and critique some of the most important scientific papers on the subject (broadly construed) of the seminar.

INTRODUCTORY COURSE DESCRIPTIONS—RECOMMENDED FOR ALL MarSE STUDENTS

201. Introduction to Marine Science (3-0-3) An introduction to the basic principles of marine science. Ocean circulation and mixing, water properties and hydrography, bathymetry of the seafloor and marine sedimentation, plate tectonics, chemistry of seawater, ocean life, biogeochemical cycles.

202. Introduction to Ocean Engineering and Technology (3-0-3) Overview of engineering topics emphasizing ocean applications. Topics include: theory, design and implementation of basic circuits used in robotic ocean instruments and autonomous underwater vehicles; basic ocean measurement and instrumentation including navigation and mapping systems; sonar systems and acoustic propagation; ocean observing systems and sensors.

203. Introduction to Management and Use of the Marine Environment (3-0-3) Uses and management efforts in the marine environment including resource conservation, environmental protection, ocean zoning and marine protected areas; decision making with respect to the marine environment; management techniques for marine pollutants; scientific, social, economic and legal issues in fisheries management; GIS applications.

MarSE COURSES LISTED BY THEME

<u>The Marine Environment</u>
MarSE 212: Fluid Dynamics of the Atmosphere and Ocean (Core)
MarSE 213: Marine Chemistry (Core) (Environmental Chemistry, EnSE 202)
MarSE 214: Air-Sea Interaction
MarSE 215: Observational Oceanography
MarSE 216: Marine Geology (Core)
MarSE 311: Coastal and Estuarine Oceanography
MarSE 313: Climate Physics and Chemistry (Climate Change, EnSE 303)
MarSE 314: Advanced Environmental Data Analysis
MarSE 315: Numerical Modeling of Geophysical Fluids (Numerical Modeling of Environmental Flows, EnSE 321)
MarSE 321: Environmental Organic Chemistry (similar to EnSE 213)

<u>Prerequisites:</u>
MarSE 211 before MarSE 212, MarSE 215, MarSE 311 and MarSE 315
MarSE 213 before MarSE 214, MarSE 313 and MarSE321
MarSE 216 before geophysics and seismology courses in ErSE

<u>Marine Life</u>
MarSE 221: Biological Oceanography (Core)
MarSE 222: Introduction to Mathematical Ecology (Core)
MarSE 223: Marine Biogeochemistry
MarSE 225: Benthic Ecology
MarSE 226: Coral Reef Ecology
MarSE 227: Marine Plankton
MarSE 322: Physical Environment of Marine Organisms

Prerequisite:
MarSE 221 before other courses within the Marine Life theme

Ocean Engineering
MarSE 231: Design Principles for Ocean Vehicles (Core)
MarSE 232: Environmental Ocean Acoustics
MarSE 233: Ocean Wave Mechanics
MarSE 234: Principles of Ocean Sensors, Instruments and Observing Systems (Core)
MarSE 332: Corrosion
MarSE 333, Nonlinear Waves and Vibrations
MarSE 335: Advanced Numerical Modeling for Marine Hydrodynamics

Management and Conservation of Marine Resources
MarSE 241: Marine Development and Management (Core)
MarSE 243: Coastal Ecology and Resource Management (Core)
MarSE 341: Aquaculture Management
MarSE 342: Political Ecology and Marine Resource Management
MarSE 343: Ecology and Management of Marine Fisheries
MarSE 344: Remote Sensing and GIS Information Systems

Prerequisite:
MarSE 241 before other courses in this theme.

Seminars
MarSE 251: Classic Papers in Oceanography
MarSE 351: Red Sea Oceanography

COURSE DESCRIPTIONS

Following are the course description abstracts. The source or exemplar is noted in parentheses after the course title, where Web pages are referenced as follows:

FAU: Florida Atlantic University, Ocean Engineering
http://www.oe.fau.edu/oe_courses.pdf

MIT: Massachusetts Institute of Technology, Open Course Ware
http://ocw.mit.edu/OcwWeb/web/home/home/index.htm

OSU: Oregon State University, College of Ocean and Atmospheric Sciences
http://www.coas.oregonstate.edu/

S: Stanford University, School of Earth Sciences
http://pangea.stanford.edu/

UM: University of Miami, Rosensteil School
http://www.rsmas.miami.edu/grad-studies/

WHOI: Woods Hole Oceanographic Institution
http://web.mit.edu/mit-whoi/www/courses/pdf/JP_course_catalog_2007.pdf

THE MARINE SCIENCE AND ENGINEERING COURSE DESCRIPTIONS

Marine Environment Courses

MarSE 212. Fluid Dynamics of the Atmosphere and Ocean (3-0-3) (Core) (MIT, 12.800) Basic concepts of fluid dynamics that will be needed as a foundation for advanced courses in atmospheric science, physical oceanography, ocean engineering, etc. Eulerian and Lagrangian description, conservation laws for continuum materials, earth's rotation, scaling analysis and simple solutions.

MarSE 213. Marine Chemistry (3-0-3) (Core) (MIT, 12.742) An introduction to chemical oceanography. Reservoir models and residence time of the major ions, inputs to and outputs from the ocean via rivers, the atmosphere and the sea floor. Biogeochemical cycling within the oceanic water column and sediments, emphasizing the roles played by the formation, transport and alteration of oceanic particles and the effects that these processes have on seawater composition. Cycles of carbon, nitrogen, phosphorus, oxygen and sulfur. Uptake of anthropogenic carbon dioxide by the oceans.

MarSE 214. Air-Sea Interaction (3-0-3) (WHOI, 12.870) Models and observations of the air-sea interface. Air-sea fluxes of heat and momentum: surface waves and large scale turbulence. Models of turbulent mixing appropriate for the surface boundary layer. Daily and seasonal cycles of stratification. Coupled modes of air-sea variability: ENSO.

MarSE 215. Observational Oceanography (3-0-3) (MIT, 12.808) The physical description of the oceans, including methods and measurements of the physical properties of seawater, the large-scale distributions of temperature, salinity, nutrients and tracers. Transport processes by mean circulation and by eddy and turbulent fluxes. Wind-driven currents and circulation of the upper ocean.

MarSE 216. Marine Geology (3-0-3) (Core) (MIT, 12.220) A survey of marine geology, with an emphasis on modern sediments and ancient sedimentary rocks. Mechanics of sediment transport and formation of sandstones, conglomerates and shales. Paleontology, with special reference to fossils in sedimentary rocks. Modern and ancient depositional environments: fossil fuels.

MarSE 311. Coastal and Estuarine Oceanography (3-0-3) (WHOI, 12.862) The circulation and dynamics of nearshore and partially landlocked marine environments. Topics include surf zone physics and radiation stress, large amplitude tidal motions and the importance of buoyancy forcing due to air-sea exchange and river runoff. The physical dynamics that lead to high biological activity are examined.

MarSE 313. Climate Physics and Chemistry (3-0-3) (MIT, 12.842) Climate in human history. Methods of climate reconstruction: ice coring, modern instrumental records and their analysis. Atmospheric chemistry: ozone and carbon dioxide and consequences for the radiation budget. Feedbacks to and from the oceans: ice cover and sea surface temperature. Models of climate: energy budget models and general circulation models.

MarSE 314. Advanced Environmental Data Analysis (3-0-3) (MIT, 12.864) Exploration and characterization of large geophysical data sets, to include some basic statistical methods such as spectral estimation, coherence and filtering. Data and model inference via state estimation and data assimilation: Kalman filtering and adjoint methods.

MarSE 315. Numerical Modeling of Geophysical Fluids (3-0-3) (MIT, 12.950) Numerical methods and parameterization used in large-scale models of the atmosphere and ocean. Modern numerical methods. Mixing processes considered include those due to mesoscale eddies and within surface and bottom boundary layers.

MarSE 321. Environmental Organic Chemistry (3-0-3) (WHOI, 1.83) This course emphasizes the processes affecting anthropogenic organic compounds in the marine environment. Uses physical chemical properties to predict chemical transfers between environmental compartments, the air, water, sediments and biota. Resulting process models are combined to predict environmental concentrations (and related biological exposures) of hazardous and natural organic compounds.

Marine Life Courses

MarSE 221. Biological Oceanography (3-0-3) (Core) (WHOI, 7.74) An overview of biological oceanography that surveys the diversity of marine habitats, major groups of taxa inhabiting those habitats and the general biology of the various taxa. Topics include the production and consumption of organic material in the ocean, as well as factors controlling those processes. Species diversity, structure of marine food webs and the flow of energy within different marine habitats detailed and contrasted.

MarSE 222. Introduction to Mathematical Ecology (3-0-3) (Core) (WHOI, 7.440) Introduces the basic models of population growth, demography, population interaction (competition, predation, mutualism), food webs, harvesting and infectious disease and the mathematical tools required for their analysis.

MarSE 223. Marine Biogeochemistry (3-0-3) (S, GP231) The processes that control the concentration and distribution of biologically utilized elements and compounds in the oceans. Processes of importance occur at the air-sea interface, the production of organic matter in the upper ocean, the remineralization of organic matter in the water column and the processing of organic matter in the sediments.

MarSE 225. Benthic Ecology (3-0-3) (OSU, OC 648) Differences between benthic and water-column biological oceanography. Historical and observational approaches including sedimentology, fluid mechanics and geochemistry.

MarSE 226. Coral Reef Ecology (3-0-3) (UM, MBF 518) Coral reef distributions and biogeography. Coral anatomy and physiology. Reef fishes and their interaction with coral communities, coral fisheries. Diseases of corals and coral bleaching.

MarSE 227. Marine Plankton (3-0-3) (OSU, OC 644) Ecology of plankton in the oceans: the limitation of growth and photosynthesis by light, nutrients and trace element availability. Removal processes. Examines primary productivity in major ocean provinces and the global ocean and the role of the marine phytoplankton in the global carbon.

MarSE 322. Physical Environment of Marine Organisms (OSU, 646) Variability in physical oceanic processes in the upper ocean and relationship to spatial and temporal variations in biomass, growth rates and other biological patterns in the ocean surface layer. The relationship between variability in ocean physical phenomena and ecosystem dynamics, including the requirements of sampling design for upper ocean ecological studies are emphasized.

Ocean Engineering Courses

MarSE 231. Design Principles for Ocean Vehicles. (3-0-3) (Core) (MIT, 2.22) This course examines the techniques used for evaluating the forces and loads over the life of a marine structure or vehicle. Loads and motions of small and large structures and their short-term and long-term statistics are studied with respect to applications.

MarSE 232. Environmental Ocean Acoustics (3-0-3) (WHOI, 2.681) Fundamentals of underwater sound, including the application to mapping and surveillance. Wave equations for fluid and elastic media. Reflection and transmission of sound at plane interfaces. Wave theory representation of acoustic source radiation and propagation in shallow and deep ocean wave guides. Numerical modeling of the propagation of underwater sound in laterally inhomogeneous environments.

MarSE 233. Ocean Wave Mechanics (3-0-3) (FAU, EOC4422) Theory of small amplitude gravity waves including wave generation, wave forecasting, mass transport and the interaction of waves with topography and shorelines. Finite amplitude waves and their effects upon moored and floating structures.

MarSE 234. Principles of Oceanographic Sensors and Instruments (3-0-3) (Core) (WHOI, 2.688) Principles of design and operation of acoustic, current, temperature, pressure, electric, magnetic and optical devices and the constraints imposed by an ocean environment. Signal conditioning and recording: noise, sensitivity and sampling limitations.

MarSE 332. Corrosion (3-0-3) (FAU, EOC6216C) Theory of corrosion based upon electrode potential and polarization. Techniques for corrosion prevention in the marine environment are studied in depth.

MarSE 333. Nonlinear Waves and Vibrations (3-0-3) (MIT, 18.377) Waves and vibrations in marine and hydrodynamic systems to include finite amplitude effects, jump phenomena, synchronization, super- and subharmonic resonance.

MarSE 335. Advanced Numerical Modeling for Marine Hydrodynamics (3-0-3) (MIT, 2.29) An introduction to numerical methods for three-dimensional hydrodynamics: differentiation, integration, solution of differential equations by numerical integration, as well as partial differential equations of inviscid hydrodynamics: finite difference methods, integral equation panel methods. Topics include lifting surface computations and the representation of deterministic and random sea waves.

Management and Conservation of Marine Resources Courses

MarSE 241. Marine Development and Management (3-0-3) (Core) (UM, MAF 516) Ocean policy development and analysis of fisheries and trade of fishery products, marine reserves and migratory species (including marine mammal) protection, development and management of aquaculture, pollution and waste trade and the development and management of tourism. The social-ecological interactions and the role and impacts of policy instruments and organizations at local, national and international levels will be examined and evaluated.

MarSE 243. Coastal Ecology and Resource Management (3-0-3) (Core) (OSU, FW 515) A survey of coastal zone and nearshore management policies, decision-making processes and management tools. Issues addressed include natural hazards, water quality, habitat protection, public access and the management of coastal development.

MarSE 341. Aquaculture Management (3-0-3) (UM, MAF 512) This course examines management practices required for sustainable aquaculture development to include environmental issues, disease prevention and control and water-quality control and recirculating sea water systems. Topics include the technology of spawning and nursery management of commercially important species of fish, mollusks and some non-traditional species.

MarSE 342. Political Ecology and Marine Resource Management (3-0-3) (UM, MAF 501) An introduction to political ecology as one approach to resource policy and management. Issues include social analysis of resource use, social change and development and the use of models of development and concepts in relation to resource use and policy formation.

MarSE 343. Ecology and Management of Marine Fisheries (3-0-3) (OSU, FW 520) Reviews basic ecological principles applied to fisheries management with the aim of promoting sustainable fisheries and marine conservation. Topics include fish life history and population dynamics and the community and ecosystem-level responses to fishing and natural variability.

MarSE 344. Remote Sensing and GIS Information Systems (3-0-3) (UM, MAF 562) Fundamentals of remote sensing to include methods of terrain mapping and analysis by means of vector and raster formatted data. Surface prediction and modeling and watershed analysis, water resource analysis and natural disaster evaluation are considered.

Seminar Courses

MarSE 251. Classic Papers in Oceanography (1-0-2)

MarSE 351. Red Sea Oceanography (1-0-2)

14. MATERIALS SCIENCE AND ENGINEERING PROGRAM

The program has three components; Core courses, Immersion courses and Specialized courses. A student seeking a M.S. degree in Materials Science and Engineering (MSE) must complete all five Core courses (MSE 201, 202, 203, 204 and 205) plus a total of 4 Immersion or Specialized courses. Students must select at least 1 course from the Immersion list (MSE 206, 207, 208 and 209) and at least one course from the Specialized list (MSE 210, 211, 212, 213 and 214). The Core courses, which will be assessed by both examination and coursework, are worth a total of 18 credit hours. Each optional course, which will consist of 28 hours of lectures and be evaluated by exam and an individual oral presentation/poster, will be worth 3 credit hours. To obtain an M.S. degree a student must accrue 30 credit points. More detailed information on degree requirements including qualifying, candidacy, dissertation and final defense is described in Section 4.

MATERIAL SCIENCE AND ENGINEERING PROGRAM COURSE DESCRIPTIONS

Core Courses

MSE 201. Fundamentals of Materials Science and Engineering (3-1-4) (42 hours taught plus 7 3-hour labs) Assessment: exam and lab reports. The course will present core knowledge of fundamental subjects in materials science and engineering, relating to material structure and structure/property relationships. Atomic theory, bonding and crystallography; electrical and magnetic behavior, including semiconductors and superconductors. Control of microstructure in metallic and ceramic materials, e.g., alloy phase equilibria, phase transformations (including liquid-solid and solid-solid) and diffusion, thermodynamic and kinetic aspects. Deformation and fracture. Polymer structure and properties: bonding, polymerization, polymer chains, rubber elasticity, glass transition, viscoelasticity, crystallization, polymer-based composites. Selection of materials for service, selection criteria and design. Electronic properties of solids: electrical conductivity of metals and alloys. Semiconductors. Superconductors and insulators. Dielectric and magnetic properties: properties of selected polymeric and ceramic dielectrics. Types of magnetic material. Crystal imperfections: point defects and their relation to non-stoichiometry, diffusion and ionic conductivity of solids.

MSE 202. Mechanical Behavior of Engineering Materials (2-2-4)
[cross-linked with ME 240]*Prerequisites*: *a standard undergraduate course in statistics and strength of materials.*

From ME 240—This course covers elastic and plastic deformation under static and dynamic loads. Prediction and prevention of failure by yielding, fracture, fatigue, creep, corrosion and wear. Basic elasticity and plasticity theories are discussed. Topics include engineering materials, structure-property relationships, elastic deformation and multiaxial loading, plastic deformation and yield criteria, dislocation plasticity and strengthening mechanisms, creep, stress concentration effects, fracture, fatigue and contract stresses. Also reviews bonding, structure and microstructure; the chemical, electromagnetic and mechanical properties of materials; and introduces the student to microstructural engineering. Experiments will include: tensile testing, strains in beams, stress concentration in notched specimens, impact testing (Charpy-type), hardness testing (indentors, Rockwell), fatigue testing (low- and high-cycle), pressure vessels, creep testing.

MSE 203. Materials Characterization and Case Study (2-2-4) (28 hours taught plus 42 hours case study) Assessment: exam and case study report. This course will introduce the basic principles of materials characterization and the common characterization techniques available. Basic principles: interaction of radiation and particle beams with matter. Images: scanning and transmission electron microscopy. Diffraction methods. Microanalysis: energy dispersive, wavelength dispersive, Auger Processes. Thermal analysis: DTA, DSC. SIMS, ESCA. The case study will be conducted in groups of four or five under the supervision of a member of academic staff. The students will be assigned an artifact and they will be expected to dismantle it, assess the design and function of the individual components, and then conduct tests to identify the material and production method used. Finally, the students will expected to suggest alternative materials and/or production methods for each component studied. The case study will be assessed by a joint report and group presentation.

MSE 204. Corrosion and Surface Engineering (3-0-3) (42 hours taught) [cross-linked with ME 342] Assessment: exam. This course will study the types of corrosion and methods of evaluation, control and behavior for both metallic and non-metallic materials. Introduction: types of corrosion. Methods of corrosion evaluation (e.g., open-circuit potential measurements and electrochemical impedance spectroscopy). Corrosion control: thermodynamic methods including Pourbaix diagrams; kinetic methods. Corrosion behavior: metals and alloys of practical interest. Marine corrosion. Reactions of glass, ceramics, polymers, biomedical materials, electronic materials and nuclear materials with severe environments. Mechanisms of corrosion including stress corrosion cracking, pitting, ion exchange, hydrolysis and their prevention. Tribology.

MSE 205. Materials Modeling (1-2-3) (14 hours taught; 28 hours computer labs) [cross-linked with ME 344] Assessment: 5 reports. This course will introduce a range of materials modeling techniques ranging from atomistic to continuum. This course will cover the theory behind all techniques and demonstrate their application using a variety of commercial and freeware software packages. This course is taught in four parts: atomistic simulation, phase equilibria, finite difference and finite element. This reflects the different length scales which materials engineers and scientists are concerned with. Overview of materials modeling. Comparison between physical and empirical models. Micromechanistic and macro-mechanistic (continuum) modeling. Advantages of modeling to the engineer. Data requirements. Interpolation/extrapolation. Curve fitting and statistical methods. Use of databanks as sources of data. Data structuring. Analytical and numerical methods. Comparison between analytical and numerical models. Computer modeling of phase diagrams: the coupling of thermochemistry, solution chemistry and phase diagrams. Application and use of commercial computer packages: Fluent, Forge2, Thermocalc.

Immersion Courses

MSE 206. Structural Ceramics (3-0-3) This course will introduce students to the processing of ceramics and glass. Powder preparation and characterization: production of powders, with emphasis on chemical routes for oxide and non-oxide materials. Powder characterization: particle shape, particle size and size distribution, specific surface area. Consolidation and forming: inter-particle forces and colloid stability. Binders and dispersants. Shaping methods: die pressing, isostatic pressing, extrusion, tape casting. Solid state sintering. Driving force and material transport mechanisms. Role of grain boundaries and pores. Grain growth and pore stability. Liquid phase sintering. Pressure-assisted sintering. Production of flat glass by the float process. Controlled crystallization of glass for glass ceramics.

MSE 207. Biomaterials (3-0-3) This course is intended for students wishing to develop an understanding of the concepts underlying the design and selection of materials for use in prostheses and implants. It focuses primarily on materials for hard tissue (bone and tooth) replacement, although some aspects of soft tissue biomaterials are also discussed. Topics covered include: reasons for implant failure, a brief introduction to relevant tissue types: anatomy, biochemistry and physiology. Concepts of biocompatibility, host response, material degradation, testing and selection, standards. Properties of hard tissue, bone structure and function, fracture toughness, measurement techniques, current research on bone biomechanics and its relevance to prosthesis design. Properties of articular cartilage, problems of replacement, osteoarthritis. Case studies, including hip and knee joint replacement, bioactive materials, soft contact lenses, artificial and prosthetic ligaments and tendons. Technology transfer, biomaterials characterization, regulatory and ethics issues.

MSE 208. Nanomaterials 1 (3-0-3) Introduction to nanomaterials. Size-dependent properties of materials. Nanometals, grain size effects and mechanical properties. Nanoporosity in metals, catalysis, porous silicon. Zero-dimensional nanomaterials, surface energy. One- and two-dimensional nanomaterials, semiconductors. Three-dimensional nanomaterials, nanoporosity, soft materials, nanocomposites. Natural nanomaterials. Top-down fabrication (including scale up). Bottom-up fabrication methods. Stability issues. Characterization methods, electron beam, scanned probe and spectroscopic techniques. Nanodevices I. Toxicity and health. Challenges and opportunities.

MSE 209. Polymeric Materials (3-0-3) [cross-linked with ME 341]

From ME 341—This course is designed for graduate students to gain a fundamental understanding of the science of polymeric materials. Beginning with a treatment of ideal polymeric chain conformations, it develops the thermodynamics of polymer blends and solutions, the modeling of polymer networks and gelations, the dynamics of polymer chains and the morphologies of thin films and other dimensionally restricted structures relevant to nanotechnology. Also provides a survey of the structure and mechanical properties of advanced engineering polymers. Topics include rubber elasticity, viscoelasticity, mechanical properties, yielding, deformation and fracture mechanisms of various classes of polymers. The course will discuss degradation schemes of polymers and long-term performance issues. The class will include polymer applications in bioengineering and medicine.

Specialized Courses

MSE 210. Electroceramics (3-0-3) Defect chemistry and Brouwer diagrams, activated hopping. Grain boundaries in semiconducting oxides. Selected technological applications including varistors. Ionic transport. Fast ion conduction and selected technological applications (fuel cells, sensors). Dielectric and ferro-electric materials. Applications of ferro-electrics in pyro-electric systems, positive temperature coefficient resistors, etc. Ceramic materials. Non-linear optical behavior, ferro-electrics in optical shutters and integrated electro optic devices.

MSE 211. Engineering Alloys (3-0-3) Materials requirements for structural applications: trade-off between properties (e.g., strength and toughness). Toughness, LEFM for structural materials, EPFM, COD, JIC, defect tolerance and design. Fatigue crack propagation: Paris law, comparison of materials, optimization of fatigue strength. Property differences between and design philosophy of steels and nickel, titanium and aluminum alloys, focusing on aerospace and automotive applications. Case studies of nickel and titanium alloy failures. Successor alloys. Alloy evolution. Hexagonal metals. Production routes. Textures.

MSE 212. Mechanical Behavior of Composite Materials (3-0-3)
[cross-linked with ME 343]

***From ME 343*—**Response of composite materials (fiber and particulate-reinforced materials) to static, cyclic, creep and thermomechanical loading. Manufacturing process-induced variability and residual stresses. Fatigue behavior, fracture mechanics and damage development. Role of the reinforcement-matrix interface in mechanical behavior. Environmental effects. Dimensional stability and thermal fatigue. Application to polymer, metal, ceramic and carbon matrix composites.

MSE 213. Materials for Energy (3-0-3) The aim of this course is to establish the key role that materials development plays in enabling energy generation in all generating technologies. The course will be delivered in terms of the four generating technologies: 1) Hydrogen and fuel cells (fuel cells, electrolysers, hydrocarbon reforming, hydrogen and energy storage). 2) Nuclear energy (fission, fusion and radiation damage/protection). 3) Hydrocarbons for the 21st century (clean coal, high temperature gas turbines, carbon sequestration). 4) Renewables (wind, tidal, solar heating and photovoltaics). Common issues that characterize and limit materials performance and cut across different technologies will be emphasized (e.g., performance at high temperatures and pressures or the response to a corrosive environment).

MSE 214. Nanomaterials 2 (3-0-3) The course will give an up-to-date view of current nanomaterials transitioning into real technological applications. It will provide the student with an understanding of the underlying nanoscience, how this is applied in technological devices and how a processing route is optimized for the properties desired. The aim is to extend this science base to industrial scale-up and quality control for device production and potential markets for nanomaterials within economic and legislative constraints. At the end of the course the students will have a good understanding of the issues that affect the industrial uptake of nanotechnology. They will have an understanding of the use of nanomaterials in a range of device applications and have an understanding of some of the ethical, environmental, technical and economic issues that are relevant to the adoption of nanotechnology solutions in society. The course will be taught as a series of case studies in nanomaterials technology, from research to processing, scale-up and industrial application. Initial studies will include: Case Study 1: Thin Film Devices; Case Study 2: Nano-photonics; Case Study 3: Semiconductor Nanoparticles (Q-Dots) for Devices; Case Study 4: Nanoparticles for Healthcare Applications. Lectures in “NanoRisk” will be given on the potential risks, environmental impact and toxicity of nanomaterials—current approaches in hazard assessment and research activity.

15. MECHANICAL ENGINEERING PROGRAM

Introduction

The Mechanical Engineering (ME) curriculum is comprised of courses in seven tracks: Controls, Design, Dynamics, Fluid Mechanics, Materials, Solid Mechanics, Thermal Science and Independent Research Study. In each such area, we specify below courses that fall into three categories, namely M.S. program courses, Ph.D. program courses and Advanced Seminar courses (course number in the 400's). Each area has one M.S. program course and between three to five Ph.D. program courses. Advanced Seminar courses are defined in each area, with precise content and prerequisites determined by the instructor. Titles and short descriptions for each course are provided below.

The M.S. program will nominally involve 3 semesters of coursework and 1 10-week internship. A M.S. student must earn at least 12 credit hours in the first semester of study (one course will be in mathematics). These will be followed by 9 additional credit hours in each of the subsequent two semesters for a total of 30 credit hours. M.S. students will be encouraged to take Ph.D. program courses and Advanced Seminar courses in the areas of the specific interests with the approval of their academic advisors and consistently with stated course prerequisites. Up to 6 credit hours taken outside of the Mechanical Engineering curriculum can count toward the M.S. degree.

At the end of the second semester of study, a Ph.D. preliminary examination will be administered to M.S. students wishing to be admitted to the Ph.D. program. Students that fail this examination will be allowed to take it for a second (and last) time at the end of the subsequent semester. Students who are admitted to the Ph.D. program will be required to take an additional 6 credit hours of course work for a total of 36 credit hours. After the fourth semester of study, Ph.D. students will take a qualifying examination, which will be in the form of a defense of their doctoral thesis proposal. A minimum of 2 semesters of research are required after a student has advanced to Ph.D. candidacy. More detailed information on degree requirements, including qualifying, candidacy, dissertation and final defense, is described in Section 4.

It is recommended that every semester, all Mechanical Engineering graduate students be required to attend a semester-long seminar series as a means of familiarizing themselves with KAUST research activities.

The courses in each track are as follows:

<u>Controls:</u>
ME 210
ME 311, ME 312, ME 313, ME 314
ME 410

<u>Design:</u>
ME 220
ME 321, ME 322, ME 323, ME 324, ME 325
ME 420

Dynamics:
ME 230
ME 331, ME 332, ME 333, ME 334
ME 430

Materials:
ME 240
ME 341, ME 342, ME 343, ME 344
ME 440

Fluid Mechanics:
ME 250
ME 351, ME 352, ME 353, ME 354, ME 355
ME 450

Solid Mechanics:
ME 260
ME 361, ME 362, ME 363, ME 364, ME 365
ME 460

Thermal Science:
ME 270
ME 371, ME 372, ME 373, ME 374, ME 375
ME 470

Course numbers for individual research or study will be available for M.S. students (ME 299) and Ph.D. students (ME 399).

Remedial courses are recommended for graduate students who may need to review standard undergraduate Mechanical Engineering material or hold an undergraduate degree in a field other than Mechanical Engineering. Such remedial courses may be offered during the summer prior to the first official semester of studies.

MECHANICAL ENGINEERING PROGRAM COURSE DESCRIPTIONS

ME 210. Control Practice (2-2-4) *Prerequisites*: *a standard undergraduate course in statistics and strength of materials.* System modeling: motivating examples from mechanics, acoustics, fluids, heat transfer, electromechanical systems. Transfer functions and state-space models. Description of feedback systems, sensitivity trade-offs and conservation laws in feedback systems. Single-input, single-output control design: Nyquist stability criterion, stability margins, compensator design using loop-shaping techniques. Anti-windup logic, reference-input prefiltering, gain-scheduling, describing functions, sampled-data control implementation. Modern control system software for design and analysis. Microprocessor interfacing: data acquisition and real-time operating systems, real-time task allocation, device drivers for sensors and actuators, familiarity with commercial systems such as DSpace, MPC555 and National Instruments. Control laboratory (12 experiments) including magnetic bearings, multi-axis position systems, high-precision positioning, pneumatic and hydraulic systems, heat exchanger and temperature control, unstable dynamics and time delays.

ME 220. Theory and Methods in Product Design (2-2-4) *Prerequisite*: *graduate standing in mechanical engineering or consent of instructor.* The engineering design process and conceptual design of products. This course provides an experience in preliminary project planning of complex and realistic mechanical engineering systems. Design concepts and techniques are introduced, and the student's design ability is developed in a design or feasibility study chosen to emphasize innovation and ingenuity and provide wide coverage of engineering topics. Design optimization and social, economic and political implications are included. Emphasis on hands-on creative components, teamwork and effective communication. Special emphasis on management of innovation processes for sustainable products, from product definition to sustainable manufacturing and financial models. The patent process. Both individual and group oral presentations are made, and participation in conferences is required.

ME 230. Intermediate Dynamics (3-0-3) *Prerequisites*: *undergraduate courses in statics and dynamics*. Particle kinematics and the kinematics of rigid body motions, classifications of forces and moments, Newton-Euler and Lagrangian formulations of the equations of motion for systems of particles and rigid bodies, solution of classical problems in rigid body dynamics and simulation of ordinary differential equations. Alternative parameterizations of the rotation of a rigid body, variational methods.

ME 240. Mechanical Behavior of Engineering Materials (2-2-4) *Prerequisites*: *a standard undergraduate course in statistics and strength of materials.* This course covers elastic and plastic deformation under static and dynamic loads. Prediction and prevention of failure by yielding, fracture, fatigue, creep, corrosion and wear. Basic elasticity and plasticity theories are discussed. Topics include engineering materials, structure-property relationships, elastic deformation and multiaxial loading, plastic deformation and yield criteria, dislocation plasticity and strengthening mechanisms, creep, stress concentration effects, fracture, fatigue and contract stresses. Also reviews bonding, structure and microstructure; the chemical, electromagnetic and mechanical properties of materials; and introduces the student to microstructural engineering. Experiments will include: tensile testing, strains in beams, stress concentration in notched specimens, impact testing (Charpy-type), hardness testing (indentors, Rockwell), fatigue testing (low- and high-cycle), pressure vessels, creep testing.

ME 250. Introduction to Viscous Flow (2-2-4) *Prerequisites*: *an undergraduate course on solving differential equations and ME 260 (can be taken concurrently).* A rigorous derivation of the governing equations, followed by illustrative solutions describing viscous incompressible flows. Cartesian vectors and tensors. Kinematics of the velocity and vorticity fields. Mass conservation in differential and integral forms. Stream function for incompressible or steady compressible flow. Cauchy equations of motion. Internal energy equation. Constitutive equation for a Newtonian viscous fluid. The Navier-Stokes and the Euler equations of motion. Vorticity equation as a necessary and sufficient condition for the equations of motion to be satisfied. Illustrative solutions: parallel flows, lubrication theory, boundary layer on a flat plate parallel to a uniform stream, Stokes flow past a sphere. Introduction to measurement methods, transducer fundamentals, instrumentation, optical systems, signal processing, noise theory, analog and digital electronic fundamentals, data acquisition and processing systems. Experiments expose students to current methods of measuring velocity: velocity profiles in the laminar boundary layer (Pitot-static tube), turbulent boundary layer (hot-wire anemometer), falling sphere in glycerin and in water (particle image velocimetry).

ME 260. Introduction to Continuum Mechanics (3-0-3) *Prerequisite*: *sophomore-level mathematics.* The course presents a broad introduction to the fundamentals of the mechanics of continuous media. In particular, it covers the kinematics of finite deformations, the concept of stress, the conservation of mass and the balance of linear momentum, angular momentum and energy. The course also discusses certain mechanical constitutive equations, such as those of the non-linear elastic solid and the Newtonian viscous fluid, including the analytical solution of simple boundary- and initial-value problems.

ME 270. Thermodynamics for Graduate Studies in Thermal Sciences (3-1-4) *Prerequisite*: *undergraduate course in engineering thermodynamics.* Axiomatic formulation of macroscopic equilibrium thermodynamics. Quantum mechanical description of atomic and molecular structures. Statistical-mechanical evaluation of thermodynamic properties of gases, liquids and solids. Elementary kinetic theory of gases and evaluation of transport properties. A brief review of power cycles. Experiments will demonstrate a Brayton cycle by converting an automobile turbocharger to a gas turbine. The statistical mechanics and quantum mechanics aspects of the course will use laser scattering and absorption to teach molecular and quantum mechanical properties of gases and liquids.

ME 299. Individual Study or Research *Prerequisites: M.S. status and consent of instructor.* Course may be repeated for credit. Maximum number of units is 3 per semester. Must be taken on a pass/fail basis. Individual investigation on topics of relevance to mechanical engineering.

ME 311. System Dynamics: Modeling and Analysis (3-0-3) *Prerequisites*: *ME 210 and AMCS 204.* Nonlinear system dynamics. Initial- and boundary-value problems, ordinary and partial differential equations. Hydrid system models;

modeling/simulation environments such as Dymola, Modelica, Ptolemy, Simulink and StateFlow. Networked system models. System analysis: elementary discretization methods, initial value, ordinary differential equation theory; linearization; convolution, state-space and frequency domain representations; stability, input/output operator norms, least squares and inverse problems; model reduction.

ME 312. Multi Input Multi Output (MIMO) Control Theory and Practice (3-0-3) *Prerequisites*: *ME 210 and ME 311 (can be taken concurrently).* Transfer functions for MIMO systems. Multivariable frequency response analysis. Input-output directions in multivariable systems: eigenvalues and singular value decomposition. System norms and introduction to MIMO robustness. Performance limitation, uncertainty and robustness for MIMO systems. Controller design for multivariable plants: linear quadratic regulator, linear quadratic Gaussian optimal control, H_∞ and H_2 control, sampled-data, model predictive control. Convex design methods: Youla parametrization, linear matrix inequalities. Multivariable control design examples in field of aerospace, automotive, chemical- and energy-efficient buildings.

ME 313. System Identification and Estimation (3-0-3) *Prerequisites*: *ME 210 and ME 311.* Deterministic state estimation, recursive observers, estimation for uncertain process dynamics; SISO and MIMO least-squares parameter estimation, linear system subspace identification. Random variables and random processes: linear systems forced by random processes, power-spectral density. Bayesian filtering including Kalman filter. Jump-Markov estimation and fault diagnosis. Nonlinear estimation, particle filters, unscented Kalman filter. Introduction to estimation for hybrid systems.

ME 314. Advanced System/Control Theory (3-0-3) *Prerequisites*: *ME 210 and ME 311*. Analysis: Lyapunov theory of stability and partial stability, general treatment of dissipative systems. Design: Adaptive control systems; nonlinear control design, including feedback linearization, dynamic inversion, sliding modes, integrator backstepping and control Lyapunov functions. Introduction to dynamic programming and Hamilton-Jacobi-Bellman equation.

ME 321. Geometric Visualization, Modeling and Optimization (2-2-4) *Prerequisite*: *basic engineering graphics*. Advanced geometric modeling with computer-based parametric solid and assembly tools. Computer-based analysis techniques for design optimization, including finite element methods for stress and deformation, tolerance analysis, vibrations and motion analysis. Technical presentation using computer animation and multimedia techniques. Design documentation.

ME 322. Mechanical Behavior of Engineering Materials (2-2-4)(Same as ME 240.) ***From ME 240—***This course covers elastic and plastic deformation under static and dynamic loads. Prediction and prevention of failure by yielding, fracture, fatigue, creep, corrosion and wear. Basic elasticity and plasticity theories are discussed. Topics include engineering materials, structure-property relationships, elastic deformation and multiaxial loading, plastic deformation and yield criteria, dislocation plasticity and strengthening mechanisms, creep, stress concentration effects, fracture, fatigue and contract stresses. Also reviews bonding, structure and microstructure; the chemical, electromagnetic and mechanical properties of materials; and introduces the student to microstructural engineering. Experiments will include: tensile testing, strains in beams, stress concentration in notched specimens, impact testing (Charpy-type), hardness testing (indentors, Rockwell), fatigue testing (low- and high-cycle), pressure vessels, creep testing.

ME 323. Introduction to MEMS (Microelectromechanical Systems) (2-2-4) *Prerequisites*: *basic electric circuits and instrumentation.* Basic understanding of integrated circuit (IC) processes and microelectromechanical systems (MEMS). Technologies including analyses, design and manufacturing processes of MEMS will be introduced. The first part of the course emphasizes IC processes including thin film deposition, lithography and etching. The second part of the course deals with micro-machining processes including surface-and-bulk micro-machining, LIGA and other processes.

ME 324. Advanced Manufacturing (3-0-3) *Prerequisite: basic undergraduate mechanics of materials.* Theory of manufacturing processes, machine tool design and process issues in quality, production rate and flexibility of manufacturing. Non-traditional manufacturing processes. Models for conventional manufacturing (material removal, joining, forming and deforming), elements of machine tool error and machine tool component design, nontraditional manufacturing processes (laser, water jet, electrical discharge machining, electro-chemical machining), rapid prototyping and process selection, optimization and planning issues. Fundamentals of high mix/low volume (HMLV) manufacturing systems including manufacturing fundamentals, unit operations and manufacturing line considerations for work in process (WIP), manufacturing lead time (MLT), economics, quality monitoring; HMLV systems fundamentals including just in time (JIT), kanban, buffers and line balancing; class project/case studies for design of competitive manufacturing systems. Laboratory term project in the application of non-traditional manufacturing processes.

ME 325. Design of Intelligent Systems (Mechatronics) (2-2-4) *Prerequisites: basic control theory, computer programming, machine design at the undergraduate level.* Smart products and use of embedded microcomputers in products and machines. Conceptual design and prototyping of mechanical systems that use microprocessors to control machine activities, acquire and analyze data and interact with operators. Machine components, actuators, sensors, basic electronic devices, embedded microprocessor systems and control, power transfer components and mechanism design. The architecture of microprocessors, as related to problems in mechanical systems through study of systems, including electro-mechanical components, thermal components and a variety of instruments. Laboratory studies of different levels of software. Building of competence in the engineering use of intelligent systems through lectures stressing small computer structure, programming and output/input operation and through laboratory work with mini- and microcomputer systems. Students will design and construct prototype products that use embedded microcomputers.

ME 331. Introduction to Nonlinear Dynamics (3-0-3) *Prerequisite: ME 230.* Qualitative methods in dynamical systems theory, perturbation methods for differential equations, nonlinear stability and bifurcation of the equilibria of dynamical systems, center manifold theory and normal forms. Application to mechanical systems. Resonance phenomena and parametric excitation.

ME 332. Advanced Nonlinear Dynamics (3-0-3) *Prerequisite: ME 230.* Dynamics of discontinuous dynamical systems, dynamics of discrete dynamical systems, grazing bifurcations, the Smale horseshoe, elementary global bifurcation theory. Application to stick-slip and friction oscillators, sliding mode controlled systems, walking machines. Numerical continuation methods and spectral analyses.

ME 333. Wave Propagation in Elastic Media (3-0-3) *Prerequisite*: *ME 261 (may be taken concurrently).* Propagation of mechanical disturbances in unbounded and bounded media. Surface waves, wave reflection and transmission at interfaces and boundaries. Stress waves due to periodic and transient sources. Acoustic detection of underground geological features.

ME 334. Dynamics of Structures (3-0-3) *Prerequisite*: *undergraduate mechanics of materials*. Modal analysis of linear multi-degree-of-freedom (discrete) and continuous models of structures. Free vibration response and response to general dynamical loads. Random vibrations. Fluid-structure interactions. Examples drawn from the response of building response to earthquake events and wave interactions with ocean-going structures (e.g., drilling platforms and ships).

ME 341. Polymeric Materials (3-0-3) *Prerequisite*: *ME 240.* This course is designed for graduate students to gain a fundamental understanding of the science of polymeric materials. Beginning with a treatment of ideal polymeric chain conformations, it develops the thermodynamics of polymer blends and solutions, the modeling of polymer networks and gelations, the dynamics of polymer chains and the morphologies of thin films and other dimensionally restricted structures relevant to nanotechnology. Also provides a survey of the structure and mechanical properties of advanced engineering polymers. Topics include rubber elasticity, viscoelasticity, mechanical properties, yielding, deformation and fracture mechanisms of various classes of polymers. The course will discuss degradation schemes of polymers and long-term performance issues. The class will include polymer applications in bioengineering and medicine.

ME 342. Deformation and Environmental Fracture of Engineering Materials (3-0-3) [Cross-listed with Imperial College's MSE 204.] *Prerequisite*: *ME 240.*

From MSE 204—This course will study the types of corrosion and methods of evaluation, control and behavior for both metallic and non-metallic materials. Introduction: types of corrosion. Methods of corrosion evaluation (e.g., open-circuit potential measurements and electrochemical impedance spectroscopy). Corrosion control: thermodynamic methods including Pourbaix diagrams; kinetic methods. Corrosion behavior: metals and alloys of practical interest. Marine corrosion. Reactions of glass, ceramics, polymers, biomedical materials, electronic materials and nuclear materials with severe environments. Mechanisms of corrosion including stress corrosion cracking, pitting, ion exchange, hydrolysis and their prevention. Tribology.

ME 343. Mechanical Behavior of Composite Materials (3-0-3) *Prerequisite*: *ME 240.* Response of composite materials (fiber and particulate-reinforced materials) to static, cyclic, creep and thermomechanical loading. Manufacturing process-induced variability and residual stresses. Fatigue behavior, fracture mechanics and damage development. Role of the reinforcement-matrix interface in mechanical behavior. Environmental effects. Dimensional stability and thermal fatigue. Application to polymer, metal, ceramic and carbon matrix composites.

ME 344. Physics-Based Modeling of Material Behavior (1-2-3) [Cross-listed with Imperial College's MSE 205.]

From MSE 205—This course will introduce a range of materials modeling techniques ranging from atomistic to continuum. This course will cover the theory behind all techniques and demonstrate their application using a variety of commercial and freeware software packages. This course is taught in four parts: atomistic simulation, phase equilibria, finite difference and finite element. This reflects the different length scales which materials engineers and scientists are concerned with. Overview of materials modeling. Comparison between physical and empirical models. Micromechanistic and macro-mechanistic (continuum) modeling. Advantages of modeling to the engineer. Data requirements. Interpolation/extrapolation. Curve fitting and statistical methods. Use of databanks as sources of data. Data structuring. Analytical and numerical methods. Comparison between analytical and numerical models. Computer modeling of phase diagrams: the coupling of thermochemistry, solution chemistry and phase diagrams. Application and use of commercial computer packages: Fluent, Forge2, Thermocalc.

ME 351. Compressible and Incompressible Viscous Flow (3-0-3) *Prerequisite: ME 250 or equivalent.* This course develops a working knowledge of fluid mechanics by analyzing the mechanisms operating in more complex, but canonical, flows. Vorticity equation and interpretation. Incompressible flow: interaction between boundary layers and large-scale flow: boundary separation on a body, spin-up, acoustic streaming. Compressible flow: sound speed, one-dimensional steady isentropic flow, shock relations, one-dimensional unsteady isentropic flow (shock formation and expansion fans quantitatively described), shock structure and thickness, flow around a corner (Prandtl-Meyer expansion), compressible boundary layers and their interaction with shocks. Dynamics of inviscid flow with vorticity (preceded by an outline of potential flow solutions).

ME 352. Physicochemical Hydrodynamics (3-0-3) *Prerequisite: ME 250 or equivalent*. Analysis of processes in which fluid flow interacts with chemistry or short-range forces. Balance laws and short-range forces. Dimensionless numbers, scaling and lubrication approximation. Effects of surface energy: Rayleigh-Plateau instability, wetting and short-range forces, effects of surface roughness, dewetting instability. Marangoni flows: effects of surfactants. Navier slip condition: moving contact lines, flow in microchannels. Effects of electric fields: electrowetting, electrokinetically driven liquid flows. Brownian motion. Diffusion and dispersion.

ME 353. Instability in Fluid Flows and Particulate Systems (3-0-3) *Prerequisite: ME 250 or equivalent.* Concepts of linear and nonlinear stability theory illustrated with examples from fluid flows and particulate systems. Introduction. Instabilities in fluids at rest. Instability in open flows. Inviscid and viscous instabilities of parallel flows. Instabilities driven by weak inertial effects: stability of a viscous phase (oil) shielded by a less viscous phase (water), stability of flow on an inclined plane. Instability in particulate systems: avalanches, ripples and dunes. Nonlinear dynamics of low-dimensional systems. Nonlinear dynamics of dispersive waves. Nonlinear dynamics of dissipative systems. Dynamical systems and bifurcations.

ME 354. Turbulence (3-0-3) *Prerequisite: ME 250 or equivalent.* Vorticity equation and the physics of turbulence. Summary of stability and transition. Description of turbulence phenomena. Tools for studying turbulence. Homogeneous turbulence, shear turbulence, rotating turbulence. Summary of engineering models. Discussion of recent advances.

ME 355. Computational Methods in Fluid Mechanics (3-1-4) *Prerequisites: an undergraduate course in fluid mechanics and ME 250 (can be taken concurrently).* Basic methods for the numerical solution of the Navier-Stokes equations for viscous and compressible flow, illustrated with examples. Introduction to numerical methods, solution of systems of linear algebraic systems, finite-difference methods, finite-volume methods. Steady flows and unsteady flows. Applications to canonical viscous incompressible flows. Complex geometries. Computation of turbulent flows. Compressible flows. Improvement of efficiency and accuracy. Boundary-integral method for creeping flow and potential flow.

ME 361. Linear Elasticity (3-0-3) *Prerequisite*: *ME 260.* Fundamentals and general theorems of the linear theory of elasticity (in three dimensions) and the formulation of static and dynamic boundary-value problems. Application to torsion, flexure and two-dimensional problems of plane strain, generalized plane stress and bending of plates. Representation of basic field equations in terms of displacement potentials and stress functions. Some basic three-dimensional solutions.

ME 362. Nonlinear Elasticity (3-0-3) *Prerequisite*: *ME 260*. Concept of an elastic material, experimental basis. Initial-boundary-value problem, useful constraints (incompressibility, inextensibility), material symmetry, strain-energy functions in widespread use, exact and approximate solutions, stability criteria and their relation to convexity conditions, elastic theory of phase transitions, small deformations superposed on large waves and oscillations. Soft-tissue biomechanics, thermoelastic response and entropic elasticity of polymers.

ME 363. Mechanics of Dissipative Media (3-0-3) *Prerequisites*: *ME 260 and ME 362.* The theory of rate-independent plasticity for metals, rocks and soils under the assumption of infinitesimal deformations. Damage mechanics with application to brittle solids. Rate-dependent theories, such as visco-plasticity and visco-elastoplasticity. Extensions to finite inelastic deformation.

ME 364. Coupled Continuum Theories of Solids (3-0-3) *Prerequisites*: *undergraduate course in physics covering basic electromagnetism and ME 260*. Introduction to the thermomechanics of solids. Theories of thermoelasticity and thermoplasticity. Diffusion of chemical species. Mixture theory. Electric charges and currents. Charge conservation, electromagnetic field, Maxwell's equations and their transformation properties. Aether relations and Lorentz transformations. Polarization and magnetization in material media. Coupling with continuum mechanics. Constitutive equations. Dielectrics, piezoelectricity, magnetoelasticity.

Variational methods. Applications to MEMS, liquid crystal displays, sensing technology, actuators.

ME 365. Finite Element Methods in Solid Mechanics (3-1-4) *Prerequisite*: *ME 260.* Weighted-residual and variational methods of approximation. Canonical construction of finite element spaces. Formulation of element and global state equations. Incremental formulations of the equations of motion. Solution of the nonlinear field equations by Newton's method and its variants. General treatment of constraints. Applications to nonlinear material and kinematical modeling on continua.

ME 371. Convective Transport (3-0-3) *Prerequisites*: *ME 250, ME 270 or consent of instructor*. The transport of heat and mass in fluids in motion, free and forced convection in laminar and turbulent flow over surfaces and within ducts. Coverage includes theory, computational tools and experimental methods.

ME 372. Thermal Radiation and Conduction (3-0-3) *Prerequisites: ME 250, ME 270 or consent of instructor.* Thermal radiation properties of gases, liquids and solids; the calculation of radiant energy transfer. Analytical methods for the determination of conduction of heat in solids.

ME 373. Heat Transfer with Phase Change (3-0-3) *Prerequisites*: *ME 250, ME 270 or consent of instructor.* Heat transfer associated with phase change processes. Topics include thermodynamics of phase change, evaporation, condensation, nucleation and bubble growth, two phase flow, convective boiling and condensation, melting and solidification.

ME 374. Microscale Thermophysics and Heat Transfer (3-0-3) *Prerequisites*: *ME 250, ME 270 or consent of instructor.* This course introduces advanced statistical thermodynamics, nonequilibrium thermodynamics and kinetic theory concepts used to analyze thermophysics of microscale systems and explores applications in which microscale transport plays an important role.

ME 375. Combustion (3-1-4) *Prerequisites: ME 250, ME 270 or consent of instructor.* Multicomponent conservation equations with reactions. Laminar and turbulent deflagrations and Rankine-Hugoniot relations. Premixed and non-premixed flames in both laminar and turbulent flows. Boundary layer combustion, ignition and flame stability. Combustion phenomena in gas turbines, spark engines, diesel engines and power plants. Numerical modeling of combustion processes. A survey of combustion-generated pollutants leading to urban air quality issues and to global warming. The experimental component of the course will use laser Raman scattering for measurement of species and temperature in laboratory flames. Principles of photon counting, gated detection and digital camera limitations will be taught. A review of optical properties of interference filters, diffraction, photon detection equipment, laser light sources will be taught. These advanced laser-based, non-intrusive diagnostics will be compared to traditional, but intrusive, measurements using suction probes and thermocouples.

ME 399. Individual Study or Research *Prerequisites: Ph.D. status and consent of instructor.* Course may be repeated for credit. Maximum number of units is 12 per semester. Must be taken on a pass/fail basis. Individual investigation on topics of relevance to mechanical engineering.

ME 410. Contemporary Topics in Control Theory and Practice *Prerequisites*: *ME 210 and consent of the instructor.* Lecture and/or seminar course on advanced topics in control theory and practice. Topics are determined by the instructor and may vary from year to year. The course may be repeated for credit. Maximum number of units is 3 per semester.

ME 420. Contemporary Topics in Design Theory and Practice *Prerequisites*: *ME 220 and consent of the instructor.* Lecture and/or seminar course on advanced topics in design theory and practice. Topics are determined by the instructor and may vary from year to year. The course may be repeated for credit. Maximum number of units is 3 per semester.

ME 430. Contemporary Topics in Dynamics *Prerequisites*: *ME 230 and consent of the instructor.* Lecture and/or seminar course on advanced topics in dynamics. Topics are determined by the instructor and may vary from year to year. The course may be repeated for credit. Maximum number of units is 3 per semester.

ME 440. Contemporary Topics in Materials Engineering *Prerequisites*: *ME 240 and consent of the instructor.* Lecture and/or seminar course on advanced topics in materials engineering. Topics are determined by the instructor and may vary from year to year. The course may be repeated for credit. Maximum number of units is 3 per semester.

ME 450. Contemporary Topics in Fluid Mechanics *Prerequisites*: *ME 250 and consent of the instructor.* Lecture and/or seminar course on advanced topics in fluid mechanics. Topics are determined by the instructor and may vary from year to year. The course may be repeated for credit. Maximum number of units is 3 per semester.

ME 460. Contemporary Topics in Solid Mechanics *Prerequisites*: *ME 260 and consent of the instructor.* Lecture and/or seminar course on advanced topics in solid mechanics. Topics are determined by the instructor and may vary from year to year. The course may be repeated for credit. Maximum number of units is 3 per semester.

ME 470. Contemporary Topics in Thermal Science and Engineering *Prerequisites*: *ME 270 and consent of the instructor.* Lecture and/or seminar course on advanced topics in thermal science and engineering. Topics are determined by the instructor and may vary from year to year. The course may be repeated for credit. Maximum number of units is 3 per semester.