Mechanical Engineering Courses Syllabi

THE FU FOUNDATION SCHOOL
OF ENGINEERING
AND APPLIED SCIENCE

Columbia University

Syllabi Table of Contents

EEME E4601 Digital Control Systems Syllabus

Professor: Professor Richard Longman
Primary contact: Email RWL4@columbia.edu

1. Course Description:
This course in digital control systems emphasizes all of the extra difficulties and considerations that are introduced by making use of a digital controller. Digital controllers necessarily sample the error signal at sample times and updates the control action at the next sample. This introduces many issues about how to create input-output models in terms of difference equations, the influence of sampling on stability, and on signal fidelity including aliasing/folding, choice of sample rate, etc. Both classical control approaches and modern or state variable control approaches are treated. To have a complete picture of the design process it is best to take EEME E6601 or EEME E3601. These courses can be taken either before or after taking digital control, but before is preferable.

2. Prerequisites:
The main basis for the mathematics used is ordinary differential equation, and there is some use of linear algebra. Material in the course is intended to refresh your memory on these topics.

3. Required Textbook: Kuo, Benjamin C., *Digital Control Systems*, 2nd edition, Oxford University Press ISBM 0-1951-2064-7
Topics from throughout the book are covered, but the lecture topics can come from many places through the book in any order.
Some homework assignments are from the book.
There are also a number of handouts specifically prepared for the class on various useful topics.

5. Grading: One Midterm Exam 45%, Final (cumulative) Exam 45%, Homework 10%.

6. Assignments: Approximately weekly homework assignments. These are important, you need to struggle with the material in order to digest it, and also to be able prepared for the exams.

7. Exam Schedule:
There are weekly 3-hour lectures. The midterm exam is usually given after the 8th lecture or the 7th lecture. Midterm exam is 3 hours.

Final exam (cumulative) is normally scheduled after all lectures have been viewed, usually scheduled by the registrar.
EEME E4601 Digital Control Systems Professor Longman
LECTURE TOPICS, RELATED HANDOUTS, RELATED BOOK SECTIONS, HOMEWORK AND EXAM TIMING
Text: Kuo, Benjamin C., *Digital Control Systems*, 2nd edition, Oxford University Press ISBM 0-1951-2064-7
Lecture 1: Introduction to feedback and digital feedback control. Block diagrams of different digital control systems. Conversion of classical feedback control laws to digital control laws
Handout: 4601ZOHandQuantizationHandout.pdf (From textbook) Book: Chapter 1 Intro
Chapter 2 pages 13-28, 55-67 (contains extra information)

Lecture 2: Solution of homogeneous ordinary differential equations (ODE), and difference equations. How to make a homogeneous difference equation whose solution is the same at sample times as the differential equation. Digital controllers as difference equations, solution of homogeneous difference equations. Desired properties of the solution, time constants, settling time, stability.
Handout: 4601SolveHomogeneousODE.pdf Homework 1

Lecture 3: Forced response of difference equations. Particular solutions of ODE and difference equations. Laplace transfer functions, ODE and transfer functions conversion, and block diagrams. Z-Transforms and z-transfer functions, conversions, block diagrams, z-transfer functions of discrete PID controllers. Particular solutions of difference equations.
Handout: 4601ParticularSolutionsODE.pdf
4601zTransformTable.pdf (from book)

Lecture 4: More discussion of solutions of ODE and difference equations, both homogeneous and particular. Block diagram algebra when all blocks are z-transfer functions. Laplace transforms, solution of difference equations using *z*-transforms. A root locus plot tuning the controller gain. Interpretation: for stability and settling time.
Book: Chapter 3.1, 3.2, 3.4; Chapter 4, pp. 124-129
Chapter 3.5-3.7 on z-transforms Homework 2

Lecture 5: Block diagram manipulation, converting a differential equation (e.g. the plant) fed by a zero-order hold, to a equivalent difference equation, finding system response using *z*-transfer functions. Rule 1 and Rule 2. Use of transform table to convert ODE to difference equations, and make block diagram contain only samples
signals – eliminating A/D and D/A. Block diagram algebra to get closed loop difference equation. Partial fraction expansions.

Handout and Book: 4601zTransformTable.pdf (again) Book: Chapter 4.3-4.4
Lecture 6: More discussion: Converting continuous elements following zero order holds to digital form. Block diagram manipulation for different cases. Finding closed loop difference equation. Aliasing.
Handout: 4601AliasingFigures.pdf Homework 3

MIDTERM EXAM
Handout: 4601WhatToKnowForMidtermAndFinal.pdf

Lecture 7: Design process: choice of controller, conversion to digital plant, finding closed loop difference equation. Three parts to the solutions: solution of homogeneous equation, particular solution for commands, particular solution for disturbances. What do you want each part of the solution to look like? Settling time seen in unit circle. Visualize solution for poles in various locations. Jury test for stability. Bilinear transformation and Routh criterion for stability.
Book: Chapter 3.3, 6.7.1, 6.7.2

Lecture 8: Derivation of transforms for holds. Develop Rule 1 using superposition and convolution sum. Develop Rule 3 to evaluate what happens between sample times.
Homework 4

Lecture 9: State space models of scalar ordinary differential equations. Solutions. Conversion to state space difference equations. Rule 1 for state space models. Derivations of entries in Table 5-1.
Handout: 4601Table 5_1TextStateSpaceEquations.pdf Book: Chapter 5.1 -5.9, 5.11, 5.12

Lecture 10: State transition matrix (exponential of a matrix) for differential and difference equations. Response between sample times. Stability of state space difference equations. Diagonalization of matrices. Rule 3 for state space models. Identification of difference equation models from input-output data.
Chapter 5.17, 5.18 Homework 5

Lecture 11: System identification. Frequency response. Nyquist. Root Locus for difference equations.
Lecture 12: Controllability, observability. Luenberger observers. State feedback and pole placement. Linear Quadratic Regulator.
Lecture 13: Bode plots, w-plane, Nyquist contour, Nyquist stability criterion. Folding. LMPC linear model predictive control.
Book: See Nyquist in text

FINAL EXAM Handout: 4601WhatToKnowForMidtermAndFinal.pdf

EEME E6601 Introduction to Control Theory Syllabus

Professor: Professor Richard Longman
Primary contact: Email RWL4@columbia.edu

1. Course Description:

This is a self-contained graduate level introduction to linear feedback control systems. It does not assume any previous course in control. The course covers both classical control design methods, and modern or state variable control methods for designing automatic control systems. It is appropriate to take this course even if you already have seem classical control in another course, because it covers a much broader set of material, and does so on a 6000 level expecting more sophistication of understanding.

2. Prerequisites:

The course makes substantial use of ordinary equations, matrix differential equation, linear algebra, similarity transformations, Laplace transforms. The course is self-contained with respect to these topics, presenting what you need to know or need to remember in these fields, but previous familiarity with these topics is very helpful.

3. MS/PhD Programs

Control systems and control system concepts are used in many fields, so the course can be relevant to students in many departments. The course designator EEME indicated that it is particularly appropriate for people in Electrical Engineering and in Mechanical Engineering, including the fields that merge the two, Mechatronics and Robotics.

Feedback control is fundamental to Aeronautics and to Astronautics, to Chemical Process Control, to Nuclear Engineering, Automotive Engineering, and gets used in various ways in Civil Engineering for structural control and structural health monitoring. It also gets used beyond engineering, in Business and in Economics – aiming to optimally manage economic growth of an economy.

4. Required Textbook:

Required Textbook, *Modern Control Engineering*, by Ogata, 5th Edition, ISBN- 13: 978- 0136156734.
Topics from throughout the book are covered, but the lecture topics can come from many places through the book in any order. Some homework assignments are from the book.
There are also a number of handouts specifically prepared for the class on various useful topics.

5. Grading:

One Midterm Exam	45%,
Final (cumulative) Exam	45%,
Homework	10%.

6. Assignments:

Approximately weekly homework assignments. These are important, you need to struggle with the material in order to digest it, and also to be able prepared for the exams.

7. Exam Schedule:

There are weekly 3-hour lectures. The midterm exam is usually given after the 8th lecture or the 7th lecture. Midterm exam is 3 hours.
Final exam is normally scheduled after all lectures have been viewed, usually scheduled by the registrar.

EEME E6601 Schedule of Lectures, Homework Assignments, and Exams
The following list of topics is a representative list, but topics can be different or in a different order for any given year. And homework assignments may be different and due at different times.

LECTURE 1:

Classical control feedback loop, scalar differential equation models, Laplace transforms and transfer functions, state variable models, state observers, and modern control feedback structure. ***Related Handouts***

- BasicStructure
- ControlDesignAndODE
- LaplaceTransforms ***Homework***

Homework #1 Relates to this lecture Due at Lecture 4

LECTURE 2:

Response to command, to disturbances, to initial conditions. Solution of homogeneous differential equations. Stability, time constants, settling time, overshoot, desired pole locations for good performance. Solution of homogeneous state space equations. ***Related Handouts***

- TransFnsAndBlockDiag
- HomogEqSol
- HomogEqSolAsTransients ***Homework***

Homework #2 Relates to this lecture Due at Lecture 4

LECTURE 3:

Particular solutions. Annihilator method. Effect of controller gains on particular solutions. Impulse response, unit step response. Number of zeros vs. number of poles. Related ***Handouts***

- ParticularSolutions ***Homework***

Homework #3 Relates to this lecture Due at Lecture 5

LECTURE 4:

State variable models, multi-input, multi-output. Controllable and observable canonical form. Similarity transformations and conversions of state variables. Numerical solution of ODE's. ***Homework***

Homework #4 Relates to this lecture Due at Lecture 6 Homeworks 1 and 2 due

LECTURE 5:

Response of classical control laws to commands, disturbances, and initial conditions. ***Related Handout***

- RoutineControlLaws ***Homework***

Homework #5 Relates to this lecture Due at Lecture 7 Homework 3 due

LECTURE 6:

Routh Criterion with special rules, use for range of stable gains, for gains producing desired settling times. Pole placement controller design for state variable models. No Handouts – Refer to Text ***Homework***

Homework 4 due

LECTURE 7:

Observable canonical form and designing Luenberger observers by pole placement. Converting observable to controllable form. The separation theorem for controller and observer design, and closed loop stability. The Kalman filter observer. ***Related Handout***

- QuadraticCostKalman ***Homework***

Homework #6 assigned Due at Lecture 8 (one week) Homework 5 due

LECTURE 8:

Kalman filter. Exponential of a matrix, the state transition matrix. Diagonalization. ***Homework 4*** assigned

MIDTERM EXAM

(3 hours, closed book. Laplace tables supplied in case wanted) ***Related Handout***

- WhatToKnowForMidterm

LECTURE 9:

Generalized eigenvectors. Jordan canonical form and exponential of matrix. Nilpotent matrix. Root locus plots for varying one parameter. ***Related Handouts***

- RootLocus

LECTURE 10:

Root locus rules. Tuning more than one gain with root locus. Root locus vs. pole placement. ***Related Handouts***

- RootLocus

LECTURE 11:

More root locus rules. Root finding. Frequency response. ***Related Handouts***

- RootLocus
- FrequencyResponse ***Homework***

Homework #7 due at Lecture 13

LECTURE 12:

Nyquist and Bode plots of frequency response. Bode plot superposition and linear approzimations. Use for response to command and bandwidth, for response to disturbances. Nyquist stability criterion. Gain and phase margin measures of degree of stability. ***Homework***
Homework 8, do not need to turn in

LECTURE 13:

Controllability. Rank of square and rectangular matrices. Observability. Controller design by Linear Quadratic Regulator.
Related Handouts

- QuadraticCostPagesFromOgata
- QuadraticCostKalman ***Homework***

Homework #7 Due

FINAL EXAM

(3 hours, closed book. Laplace tables supplied in case wanted) Scheduled by Columbia Registrar ***Related Handout***
• WhatToKnowForFinal

MEBM E4439 – Modeling and Identification of Dynamic Systems

Professor: Nicolas W. Chbat, PhD

Teaching Assistant: Cheng Bi

Week	Topic	Hours
1	Fluid Systems, Physical Laws	3
2	Generalized Dynamics System Modeling, Linear Systems, Convolution, Impulse and Step Responses, State-Space Matlab/SIMULINK*	3
3	Nonlinearities, 3rd and higher order systems	3
4	Thermal Systems, Mechanical Systems	3
5	Mechanical Systems (cont'd)	3
6	Electrical and Diffusive Systems	3
7	Hybrid Systems, Transformers, Gyrators	3
8, 9	Classical & Non-parametric System Identification, Z-transform	6
10, 11	Stochastic signals, Parametric System Identification	6
12, 13	Kalman Filter, Observer-Kalman Identification (OKID)	6
Extra	Lab session: Matlab's System ID Toolbox*, Review	2

Grade:
Homework: 40%
Exam 1: 25%
Exam 2: 35%
Total: 100%

There will be ~10 homework sets and 2 exams. Exam1 is a modeling project.

Textbooks (suggested – also on reserve in library):

1. Rowell, Wormley *System Dynamics, An Introduction*

2. Chow, Frederick, Chbat *Discrete-Time Control Problems using Matlab*

3. **DiStefano III** *Dynamic System Biology Modeling and Simulation*

4. Iserman, Munchhof *Identification of Dynamic Systems, Introduction with Applications*

Rationale: Articulating real-world dynamics mathematically, i.e. modeling, is often half of the battle in solving engineering problems. Understanding different modeling approaches (based on data, rules, physics, or probabilities) and their applicability is an invaluable tool to the practicing engineer. Quickly obtaining ordinary differential equations of a dynamic system and estimating its parameters from experimental data (system id or parameter estimation), sets the engineer apart. A model thus obtained can be readily used for prediction, diagnosis, or controller design.

MEBM E4710 Morphogenesis: Shape and Structure in Biological Materials

Office Hours Prof. Kasza: TBA, Mudd 220C (and by appointment, karen.kasza@columbia.edu)

Prerequisites

Courses in mechanics, thermodynamics, and ordinary differential equations (for example ENME 3113, MECE E3301**,** and MATH UN3027) at the undergraduate level or instructor's permission.

Description Introduction to how shape and structure are generated in biological materials using an engineering approach that emphasizes the application of fundamental physical concepts to a diverse set of problems. Mechanisms of pattern formation, self-assembly, and self- organization in biological materials, including intracellular structures, cells, tissues, and developing embryos. Structure, mechanical properties, and dynamic behavior of these materials. Course uses textbook materials as well as a collection of research papers.

Textbooks For course readings, I am requiring:

• *Mechanisms of Morphogenesis*, 2nd Edition, Jamie Davies (required)

Other texts that may be helpful:

• *Biological Physics of the Developing Embryo*, 1st Ed., by Forgacs and Newman, Cambridge University Press, 2005.
• *Molecular Biology of the Cell*, 6th Ed., by Alberts et al., Garland, 2014.
• *Physical Biology of the Cell*, 2nd Ed., by Phillips, Kondev, Theriot, and Garcia, Garland Science, 2012.
• *Mechanics of Motor Proteins and the Cytoskeleton*, by Jonathan Howard, Sinauer, 2001.

Course structure

The course will consist of lectures and in-class discussions of research papers. For in- class discussions, you should read the papers well ahead of time and prepare a "reading memo" that will help you prepare for the discussion (details to follow).

Homework

Homework and paper readings will be assigned every one or two weeks.
Homework and reading memos must be submitted electronically via Courseworks as a pdf file.

You are encouraged to discuss with the TA and the instructor. You may discuss with classmates, but the work you submit should be your own. Copying homework from other students is unacceptable, against University regulations, and will be dealt with according to University policy. **You may not consult solutions from past years, online, or from textbook solutions.**

Final presentation Each student will read and present a research paper to the class. I will post suggested papers. You are encouraged to use one of these papers for your presentation, but if you have another paper you would like to present, you may propose it to me for approval.

Phones Cell phone use is not allowed during class.

Grading

• 35% Homework
• 25% Reading memos
• 15% Participation in in-class discussions
• 25% Final presentation

Important Note I would like to notify all individuals with access to the MEBM E4710 course materials that the course material is copyrighted and is not to be freely distributed/posted online without the written consent of the professor. I explicitly deny consent to the posting of the lecture slides, exams, assignments and answers to any assignment or exam on any website outside of Columbia University's Canvas (a.k.a Courseworks2). Notice has been provided directly to Course Hero that they are not to accept any course content from this course for the current and for the past semesters. Providing and posting such content is in violation of the Digital Millennium Copyright Act.

MEBM E6310 MIXT THEORIES FOR BIOL TISSUES

Notice:

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Academic Integrity

The follow constitutes cheating:

- Copying assignments from others.
- Consulting solutions sets and laboratory reports from previous years.
- Consulting exams from previous years that were not made available by instructor.
- Completing individual assignments in a group, when permission not explicitly granted by instructor.
- Plagiarizing the work of others.
-

Cheating may lead to the following consequences:

- Student receives a failing grade for a specific assignment.
- Student receives a failing grade for an entire course.
- Student may be expelled from the university.
- The Department of Mechanical Engineering adheres to Columbia's policies on academic integrity, see http://www.college.columbia.edu/academics/integrity.

Student Bill of Rights

- Academic integrity policies clearly explained at start of semester
- Course requirements/grading policies/etc. must be clearly stated at start of semester.
- Textbook/reference book usage must be clarified at start of semester.
- Homework assignments will be graded on a weekly basis (unless valid explanation provided).
- Midterm exams will be graded within two weeks of test (unless valid explanation provided).
- Final exams will be graded within the deadlines set by the university.
- Instructor and teaching assistants must provide office hours or otherwise explain procedure for meeting with students.
- Instructors will provide pertinent information on assignments and lab reports in a timely manner.

Honor Code

- Honor code: **https://www.cc-seas.columbia.edu/integrity (https://www.cc-seas.columbia.edu/integrity)**
- Also review the guidelines posted here: **http://www.columbia.edu/cu/studentconduct/documents/StandardsandDiscipline.pdf (http://www.columbia.edu/cu/studentconduct/documents/StandardsandDiscipline.pdf)**
- All coursework is to be done by the student working alone. For homework assignments, you may consult other students for general guidelines or to review and discuss material covered in class, but homework assignments must be completed individually.
- No external aids or electronic devices are allowed in exams.
- Do not look up homework solution sets posted from previous years or posted elsewhere.
- Consult the instructor if you require clarifications regarding the honor code.

Course Grading

- Homeworks 30%
- Midterm Exam 30%
- Final Exam 40%

Chapter 1: Mixture Theory

- History
  - The theory of mixture
  - Mixture theory for biological tissues
- Basic definitions in mixture theory
  - Apparent and true mass densities
  - Molar concentration
- Simplifying assumptions for biological tissues
  - Intrinsic incompressibility of constituents
  - Electroneutrality
  - Isothermal conditions

        - Constrained mixtures of solid constituents
        - Negligible fluid viscosity and solid viscoelasticity

Chapter 2: Tissues Modeled as a Mixture of a Solid and a Fluid
- Introduction
- Governing equations of a solid-fluid (biphasic) mixture
    - Overview
    - Mass balance
    - Stress tensor of mixture constituent
    - Momentum balance
    - Energy balance
    - Entropy inequality
    - Kinematics of the continuum
    - Constitutive assumptions
    - Implications for momentum balance
    - Frictional drag between fluid and solid constituents
    - Linear isotropic elastic solid
    - Summary of governing equations
- Boundary conditions
    - Mass jump across an interface
    - Momentum jump across an interface
    - Energy jump across an interface
    - Summary of boundary conditions
- Permeation
    - Steady-state permeation
    - Transient response
- Confined compression
    - Creep
    - Stress-relaxation
- Unconfined compression
    - Solution by the method of Laplace transform
        - Initial and equilibrium responses
        - Transient response
- Transport across thin membranes

Chapter 3: Solute Transport in Biological Tissues
- Introduction
- Governing equations for a solid-solvent-solute mixture
    - Constitutive assumptions
    - Implications for momentum balance
    - Frictional drag
    - Chemical potential of ideal solutions
        - Fluid mixtures
        - Solid-fluid mixtures
    - Chemical potential of non-ideal solutions
    - Solubility and partition coefficient
    - Diffusion coefficients and Fick's laws for dilute solutions
- Summary of governing equations
- Boundary conditions
- FEBio tutorial

Course Summary:

Date	Details	Time
Wed Jan 29, 2020	HW 01 **https://courseworks2.columbia.edu/courses/95904/assignments/404587**	4:10 pm
Wed Feb 5, 2020	HW 02 **https://courseworks2.columbia.edu/courses/95904/assignments/408288**	4:10 pm
Wed Feb 19, 2020	HW 03 **https://courseworks2.columbia.edu/courses/95904/assignments/413051**	4:10 pm
Wed Feb 26, 2020	HW 04 **https://courseworks2.columbia.edu/courses/95904/assignments/415759**	4:10 pm
Wed March 4, 2020	HW 05 **https://courseworks2.columbia.edu/courses/95904/assignments/417622**	4:10 pm
Wed Apr 1, 2020	**MidtermExamination https://courseworks2.columbia.edu/courses/95904/assignments/421604**	4:10 pm
Wed Apr 15, 2020	HW 06 **https://courseworks2.columbia.edu/courses/95904/assignments/432255**	4:10 pm
Wed May 13, 2020	**Final Examination** **https://courseworks2.columbia.edu/courses/95904/assignments/4430297 pm**	

MECS 4510 – Evolutionary Computation and Design Automation

1. **Credits:** 3
2. **Contact Hours:** 2.5 hours/week
3. **Instructor's or course coordinator's name: Hod Lipson**
4. **Textbook Information:** Melanie Mitchell, (1996) An introduction to genetic algorithms,

   MIT Press

   a. **Other Supplemental Materials:** Lecture slides

5. **Specific Course Information**

   a. **Course Description:** Covers fundamental and advanced topics in evolutionary algorithms and their application to open-ended optimization and computational design. Covers genetic algorithms, genetic programming, and evolutionary strategies, as well as governing dynamics of co-evolution and symbiosis. Includes discussions of problem representations and applications to design problems in a variety of domains including software, electronics, and mechanics.
   b. **Prerequisites:** Programming Experience
   c. **Co-requisites:** N/A
   d. **Course Required or Elective:** Elective

6. **Specific Goals for the Course**

   a. **Specific Outcomes of Instruction:** The student will be able to understand and apply evolutionary computation techniques to solve global optimization problems in engineering design.
   b. **Student Outcomes Addressed by Course:** a, b, c, e, k, m

7. **Brief list of topics to be covered**

   1. Optimization background and terminology: Gradient optimization methods, sampling methods, linear programming, combinatorial optimization.
   2. Evolutionary Biology background and terminology: Genotype and phenotype, unit of selection, genes and traits, chromosomes, alleles, diploid and haploid, fitness, mutation and recombination. Selection, variation and landscapes. The strengths and weaknesses of the evolutionary model. Inductive bias. The "No free lunch" theorem.
   3. Genetic Algorithms: Representation, operators, and standard algorithm. The building block hypothesis and the schema theorem.
   4. Evolutionary strategies: Evolution in continuous variables. Transformations.
   5. Genetic Programming. Building blocks and architecture-altering operators. Libraries and Trees.
   6. Selection mechanisms: Fitness proportionate, rank, tournament, Stochastic Universal Sampling and Boltzman selection methods. Niching methods. Spatial methods. Consequences of selection models.
   7. Artificial landscapes and test functions: The Two-armed bandit problem. Multi-modal and deceptive functions. Royal roads. N-k landscapes. Hierarchical and fractal functions. Pareto evolution.
   8. Co-evolution: Multiple populations and single-population co-evolution, relative and absolute fitness, engagement and gradient loss, the red queen effect. The credit assignment problem.
   9. Evolutionary dynamics and game-theoretic models: Evolutionary stable states, cycles and chaos. The iterated prisoner's dilemma. Evolution of cooperation.
   10. Evolution and learning: Plasticity and life-time learning. Lamarckian learning, how learning can guide evolution. The Baldwin effect.
   11. Symbiosis as a source of evolutionary innovation. Macro-mutations, Major transitions in evolution, symbiosis and symbiogenesis. How symbiosis can guide evolution.
   12. Evolutionary algorithms as models: Modeling sexual selection, modeling ecosystems, artificial life.
   13. Evolutionary robotics and evolutionary hardware: Evolving control. Evolving morphology. Body-brain co-evolution. Evolution in simulation and in reality. The case for and against simulation.
   14. Modularity and regularity in evolution. The scaling problem and the curse of dimensionality. Evolvability. Module acquisition. Developmental models. Compositional and hierarchical approaches.
   15. Swarm intelligence, particle swarm optimization
   16. Estimation exploration approaches for model inference

MECS 6616 - Robot Learning

Prof. Matei Ciocarlie

This class aims to provide an overview of the machine learning tools and methods available at your disposal for various Robotics (and more general engineering) problems. We will study multiple major families of algorithms, including supervised and unsupervised learning, deep learning, and reinforcement learning. We will primarily focus on the conceptual and practical aspects of these methods as they relate to Robotics problems but will also cover some aspects of the underlying ML theory when it is useful or needed for a rigorous understanding.

While an introductory Machine Learning class (such as COMS W 4771) constitutes useful background, it is not a prerequisite, as this class will introduce the needed machine learning concepts from the ground up. Compared to dedicated classes (e.g. Machine Learning, Deep Learning, or Reinforcement Learning), we will go into less detail on the mathematical workings of the ML algorithms, but cover more types of algorithms, and look at practical applications in Robotics.

The course will consist of three parts:

- Part 1: Dimensionality reduction, classification and regression
- Part 2: Deep Learning and learning in Computer Vision
- Part 3: Reinforcement learning

Lectures dedicated to discussions of recent and seminal papers in the field will be interspersed throughout the semester. Approximately 30% of the class will consist of paper discussions.

Grading

- Three programming projects, one for each part of the class: approx. 60% of the grade
  - All projects will require the use of Python3, Ubuntu 18.04, and SVN.
  - You will use libraries such as scikit-learn, PyTorch, etc.
  - There will be no skeleton code. You will start from blank files.
- Two written exams: approx. 40% of the grade
  - Primarily conceptual questions, with occasional mathematical details required

Example syllabus

- Introduction: what is ML?
- Clustering
- Dimensionality Reduction
- Dimensionality Reduction II
- Supervised Learning I
- Supervised Learning II
- Paper Discussions
- Computer Vision I
- Computer Vision II
- Paper Discussions
- Paper Discussions
- Deep Learning I
- Deep Learning II
- Deep Learning III
- Paper discussions: Deep Learning in Robotics
- Deep Learning: CNNs
- Deep Learning: AEs, RNNs
- Paper discussions: AEs and RNNs
- RL I (Intro, Q-learning)
- RL II (Policy Iteration)
- RL III (Deep Q-Networks)
- RL IV (Policy Gradient, Actor-Critic)
- Paper discussions: RL in Robotics
- Introduction to software tools: MuJoCo, Gym, Baselines, Garage
- Paper discussions: RL in Robotics

ME E4058 - Mechatronics & Embedded Microcomputer Control
Fall 2020

Instructor: Dr. Enrico Zordan
E-mail: ez2287@columbia.edu

TA / Course Assistants (CA) (for both Lab Sessions):
tbd tbd@columbia.edu
tbd tbd@columbia.edu
tbd tbd@columbia.edu

Mechatronics Class Hours: Maximum Lab Enrollment 30

Lecture:	Thursday	4:10 – 6:40	Mudd 337
Lab:	Thursday	7:00 – 9:30	MechTech ET 273

Course Description:
What constitutes a successful mechanical product design in today's world where electronics and computers are found everywhere? This course addresses this question. Mechatronics, as an engineering discipline, is the synergistic combination of mechanical engineering, electronics, control engineering, and computer software, all integrated through the product design process. Starting at concept and continuing through manufacture, mechatronic designs optimize the available mix of technologies to produce quality precision products and systems in a timely manner with features that the customer wants. If successful product designs are to be produced in today's environment, it is imperative that electronics and computer software be included in the design process when the basic product functions and properties are defined. The real benefits to industry of a mechatronic approach to product design are shorter development cycles, lower costs, and increased quality, reliability, and performance. This course covers mechatronic system design, analysis of dynamic systems, control sensors and actuators, analog and digital control electronics, interfacing sensors and actuators to a microcomputer, discrete and continuous controller design, and real- time programming for control. These are the fundamental areas of technology that determine successful mechatronic designs. Emphasis is placed on physical understanding and design issues rather than on mathematical formalities. Throughout the coverage, the focus is kept on the role of each of these areas in the overall design process and how these key areas are integrated into a successful mechatronic system design.

Course Layout:
Mechatronics Syllabus
This course is organized in a combined lecture / laboratory format. Lectures are designed to introduce the material and to show how the course material can be used to solve real world design problems. Laboratory session address case studies in mechatronic product design. Rather than concentrating on a single product, the case studies deal with general techniques which can be applied in a wide variety of product areas.

Prerequisites:

Basic Knowledge of:
- Dynamic Systems Analysis
- Circuits, Electronics and Instrumentation
- C Programming

Course Objective:
Product design is one of the few engineering activities that have not been outsourced to countries outside the United States. The "mechatronics engineer" is that rare individual who has a genuine interest and ability to span a wide range of technologies, and who takes delight in working across disciplinary boundaries. The mechatronics engineer can identify and use the particular blend of technologies which will provide the most economic, elegant, and appropriate solution to the product design problem at hand. To be able to evaluate concepts generated during the design process, without building and testing each one, the mechatronics engineer must be skilled in the modeling, analysis, and control of dynamic systems and understand the key issues in hardware implementation. This course studies, in depth, the key areas of technology on which successful mechatronic designs are based and thus lays the foundation for the students to become true mechatronic engineers.

The objective of this course is for the student to be competent in the following areas:
- Mechatronic System Design Principles (discussed throughout the course)
- Analysis of Dynamic Physical Systems (discussed primarily in lecture)
- Embedded Microcomputer Control System Design
- Analog and Digital Control Electronics
- Digital Data Acquisition and Waveform Generation
- Control Sensors and Actuators

• Interfacing Sensors and Actuators to Microcomputers
• Real-Time Programming in Assembler and Embedded C
• Advanced Concepts (e.g. fuzzy logic control, active materials as sensors and actuators)

In addition, this course:

1. provides students with industrial design experience. Students learn product design by experience, implementing solutions for case studies on real world design problems. Each case study contains a specific set of design objectives that must be met.

2. fosters team building. Students are divided into two-person lab teams. Case studies require significant work extending over several weeks. Assignments require the planning, delegation of tasks, coordination and communication required of a team effort.
3. enhances student skills related to all elements of engineering design methodology, including analysis, modeling, simulation, experimentation and satisfying design constraints.
4. has each team of students execute several engineering design projects using embedded microcomputer control.
5. teaches the application of analog and digital electronics, microcomputers, and control sensors and actuators through laboratory experimentation. All case studies involve electronic feedback control of mechanical systems requiring the integration of electronic, computer, control and mechanical components.

Textbook:
Course notes written by the instructor serve as the textbook for the course. These will be supplemented with sections from various published sources and information from internet locations.

References: (not to be purchased)

Mechatronics

1. *The Art of Embedded System Design,* Ganssle, J., Newnes, 2nd edition, Butterworth-Heinemann, 2008. (on reserve in the library)
2. *Art Of Electronics*, Horowitz, P. and Hill, W., 3rd edition, Cambridge University Press, 2015. (on reserve in the library)
3. *Mechatronics with Experiments (Coursemart)*, Centinkunt, S., 2nd edition, 2015. (on reserve in the library) 4. *Mechatronics: an Integrated Approach*, de Silva, C. W., CRC Press, 2005. (on reserve in the library)
5. *Introduction to Mechatronic Design*, Carryer, J.E., Ohline, R.M., & Kenny, T.W., Prentice Hall, 2011.
6. *Getting Started in Electronics*, Mims, III, F.M. 1997 (on CourseWorks)
7. *Mechatronics: Electronic Control Systems in Mechanical and Electrical Engineering,* Bolton, W., 5th Edition, Addison Wesley Longman. 8. *Introduction to Mechatronics and Measurement Systems,* 2nd edition, Alciatore, D. & Histand, M. McGraw Hill, 2003.
9. *Dynamic Modeling and Control of Engineering Systems, Second Edition,* Shearer, J.L., Kulakowski, B.T. & Gardner, J.F., Prentice Hall, 1997.
10. *Modeling and Analysis of Dynamic Systems, Second Edition,* Close, C. & Frederick, D., Houghton Mifflin Co., 1993
11. *Control Sensors and Actuators*, C.W. deSilva, Prentice-Hall, 1989. (on reserve in the library)
12. *Mechatronics System Design,* Shetty, D. and Kolk, R., PWS Publishing Co., 1997.
13. *Design with Microprocessors for Mechanical Engineers*, A.K. Stiffler, McGraw-Hill, 1992.
14. *Measurement Systems*, E.O. Doebelin, 4th Edition, McGraw-Hill, 1990.

15. *Feedback Control of Dynamic Systems*, Franklin, G., Powell, J., and Emami-Naeini, A., 7th Edition, Addison-Wesley, 2014.
16. *Control System Design: An Introduction to State-Space Methods*, Friedland, B., Dover Books, 2005

C Programming

1. *The C programming Language,* Kernighan, B. W. & Ritchie D. M., Prentice Hall, 1988. (on reserve in the library)
2. *C Language for Programmers,* Pugh, K., QED Information Sciences, 1989. (on reserve in the library)

Lecture Topics: *Topics are covered using both Lecture and Case-Study. Case Studies emphasize a Problem-Solving Approach with Hands-on Laboratory Exercises and Hardware Demonstrations.*

1. Introduction to Mechatronics
2. Mechatronic System Design (discussed throughout the course)
3. Digital Electronics (digital logic, timing circuits and state machines)

4. Analog Electronics (op amps and filters)
5. Data Acquisition Systems
6. Laboratory Equipment (mixed signal oscilloscope, power supplies, function generator, digital multimeter)
7. Embedded Microcomputer Architecture & Microcomputer Development Systems
8. Control System Design (use of MATLAB) 9. Control Sensors and Actuators
10. Interfacing Sensors, Actuators to Microcomputers
11. Real-Time Programming in Assembler and Embedded C
12. Advanced Concepts (e.g. electromagnetic levitation, fuzzy logic control, active materials)

Laboratory Exercises and Case Studies:
Laboratory sessions involve completing exercises and case studies. Exercises are one week sessions intended to develop specific skills. These are not graded but must be completed and demonstrated to the instructor or teaching assistant.

Mechatronics is primarily taught through the use of case studies. Case studies are graded and span multiple weeks. The purpose of these case studies is to help develop in each student the experience of designing real world mechatronic products. The key issues of software simulation, hardware implementation, and comparison of analysis and experiments are investigated. The *defining quality* of a mechatronics engineer is the ability to work competently in the three areas of engineering: analysis, design and experimentation. Hands-on hardware exercises include:
1. Laboratory Equipment
2. Microcomputer Development Systems

3. C Programming

Case studies include:
1. Digital Electronics and Logic Systems
2. Analog Electronics, OpAmps and Filters
3. Electromagnetic Levitation
4. Interfacing Microcontrollers
5. Programming Microcontrollers in Assembly and C
6. Digital Input / Output System (Solenoid) - - On / Off Control, Timing Control
7. Stepper Motor - - Open-Loop Position Computer Control, State Machines
8. DC-Motor - - Closed-Loop Velocity Control

Students will conduct laboratory exercises in 2 person teams. A set of questions will be provided with each laboratory exercise to be answered during the session and submitted for grading. These questions are meant to emphasize key points of the exercise and to provoke thought about possible extensions to the work. For each microcomputer case study, question sets will be graded and will count 5% of the final grade. One set of questions will be turned in for each lab team. In addition, programs written in Assembler and C will be turned in electronically (either by email or diskette) and will count 45% of the grade. Grades for programs will be based on following the firmware standard, program content, program organization, speed of execution and the use of comments to document the code. Finally, the laboratory team must demonstrate the operation of the embedded program to the instructor. The system must perform all the requirements set forth in the case study and operate reliably. In some case studies, specific programming techniques will be required. Operation of the system will count 50% of the case study grade.
The programming case studies will use several microcomputers from Microchip Corporation. Microchip is the largest manufacturer of microcomputers for mechatronic applications. Devices include internal timers, counters, analog-to-digital (A/D) converters and pulse width modulators (PWM), which are all useful for controlling mechanical systems. Ports can be configured for different purposes under software control. The microcomputers from Microchip are Very Long Instruction Word (VLIW), Harvard architecture Reduced Instruction Set Computers (RISC). Since programming is first done in Assembler, students learn microcomputer operation at the register / bit level. With this background, their embedded C programs are much more efficient.

***Homework Assignments*:**
Homework will be not be specifically assigned. However, students are expected to review all distributed material outside of class since this material cannot be covered completely in lecture. Further, case studies have to be completed in the scheduled time and student teams are expected to complete case study assignments outside of lab time if they cannot be completed in the required period. Arrangements can be made with the instructor and TA to complete case studies outside class time.

The microcomputer development system is available online at www.microchip.com; the C compiler is available as a 1-month demo from Microchip. Much of the work on the case studies can be accomplished outside of lab.

Exams:
There will not be a final assignment in this course. There is also no mid-term exam.

Quizzes:
Brief on-line quizzes will be conducted during the course. The quizzes are meant to test whether the course material is understood and to gauge the effectiveness of course notes. Quizzes will count 10 % of the final grade.

Class Attendance and Participation:
Attendance at ***all*** classes is mandatory and participation in class is strongly encouraged. An effort will be made to make all classes interactive and thus greatly enhance the learning process. In addition, the instructor will consider preparation and participation in class, lateness and attendance, as well as professional behavior, for all students in the final grade. This evaluation will be used by the instructor to either raise or lower the student's overall letter grade in marginal cases.

***Course Conduct*:**
Student-teacher relationships are built on trust. Acts, which violate this trust, undermine the educational process. For example, students must trust that teachers have made appropriate decisions about the structure and content of the courses they teach, and teachers must trust that the assignments that students turn in are their own work.

In this class, all assignments that are turned in for a grade must represent the student's or the laboratory team's own work. Collaboration with other members of the class is encouraged since this aid in the learning process. However, each laboratory team is expected to submit a unique assignment that is representative of their work. Submission of any assignment that is in violation of this policy will result in a penalty of zero for that particular assignment. If you have any questions concerning this policy before submitting an assignment, please ask for clarification. Also, any cheating on an electronic quiz or exam will result in a grade of zero for that particular quiz or exam. In addition, students are expected to conduct themselves in a professional manner at all times.

Grade Summary:

Case Studies		90%
Digital Logic	5%	
On / Off Control	25%	
Other Case Studies	20%	
Electronic Quizzes		10 %
Total		**100 %**

***Grade Appeal*:**
Mechatronics Syllabus
Students are encouraged to discuss their grades with the instructor as frequently as needed. The student is always given the benefit of the doubt in all grade discussions and every effort will be made to find ways to help a student improve his/her grade throughout the semester.

MECE E4100 Mechanics of Fluids Course Meeting Times

MECE E4100: Mechanics of Fluids

Vijay Vedula

Spring, 2022

Class Room: Mudd 327
Class Hours: Wed 4:10-6:40p
mail: vv2316@columbia.edu
Course Assistant: TBA

Office: Mudd220BA
Office Hours: TBA E-

Course Description

This is an intermediate-level fluid dynamics course that introduces and develops the fundamental principles governing the flow of fluids and its applications. Topics include basic continuum mechanics, dimensional analysis, transport theorem and control volume analysis, the Navier- Stokes equations, flows at low and high Reynolds numbers, boundary layers and secondary flows, introduction to transition and turbulence, vorticity dynamics, ideal/potential flows, and additional selected topics (aerodynamics, turbomachinery, biofluids).

Textbooks

For the course readings, I strongly recommend:

- P.K. Kundu, I.M. Cohen, & D.R. Dowling, Fluid mechanics. 6^{th} ed. Academic Press, 2015.
- Panton, Incompressible Flows, 4^{th} ed., Wiley, 2013.

Recommended additional reading:

- F. White, Fluid Mechanics, McGraw-Hill, 2015.
- G. K. Batchelor, An Introduction to Fluid Dynamics, Cambridge University Press.
- Milton van Dyke, An Album of Fluid Motion, Parabolic Press, 1982.
- Theodore von Kármán, The Wind and Beyond, Little Brown and Company, 1967 (for fun and historical perspective of classical fluid mechanics).

Videos: National Committee for Fluid Mechanics Films

Prerequisites

MECE E3100 or equivalent

Grading

- Homework (40%)
- Exam I (25%)
- Exam II (35%)

Schedule and Weekly Syllabus

The schedule is tentative and subject to change during the course.

Week 1 (Jan 19):

- Review of key concepts from fluid mechanics
- Mathematical concepts
- Introduction to dimensional analysis

Week 2 (Jan 26):

- Kinematics: Lagrangian and Eulerian descriptions
- Control volume analysis
- Reynolds Transport Theorem

Week 3 (Feb 02):

- Dynamics of inviscid flows
- Bernoulli's principle
- Streamline coordinates
- Euler-s and Euler-n equations

Week 4 (Feb 09):

- Applications of control volume analysis and Bernoulli
  - Momentum theorem, jets and jet pumps, wakes, sudden expansions, etc.
  - Moment of momentum theorem (lawn sprinkler example)
- Effects of compressibility
- Unsteadiness (unsteady Bernoullli)
  - Pipe connected to a large tank
  - Bubble expansion in an infinite fluid (Rayleigh's equation)

Week 5 (Feb 16):

- Introduction to viscous effects
- Couette flow, plane Poiseuille flow
- Unsteady flows (Rayleigh's 1^{st} and 2^{nd} flows, Womersley flow)

Week 6 (Feb 23):

- The Navier-Stokes equations
- Inertia-free flows (low Re, Stokes flow)
- Introduction to viscous boundary layers (high Re)

Week 7 (Mar 02):

- Solutions to boundary layer equations (Blasius, Falkner-Skan)
- Similarity solutions
- Momentum integral equation (von-Ká rmá n - Pohlhausen's approach)
- Secondary flows

Week 8 (Mar 09): Exam I

Week 9 (Mar 14 - Mar 18): Spring Break

Week 10 (Mar 23):

- Introduction to stability and transition
- Linear stability analysis
  - Kelvin-Helmholtz instability
  - Stability analysis for nearly-parallel viscous flows (Orr-Sommerfeld equation)
  - Inviscid instability (Rayleigh's and Fjortoft's criteria)
- Introduction to turbulence
  - Characteristics
  - Governing Equations (RANS)

Week 11 (Mar 30):

- Turbulence
  - Closure problem
  - Correlations, mean and turbulent kinetic energy
  - Energy cascade, Kolmogorov's theory
- Introduction to vorticity dynamics
  - Helmholtz's decomposition
  - Vorticity transport equation

Week 12 (Apr 06):

- Vorticity dynamics
  - Significance of vortex stretching
  - Kelvin-Helmholtz circulation theorem
  - Biot-Savart law
- Potential flows
  - Mathematical formulation
  - Classical examples (plane flows, source/sink, vortex, dipole, cylinder in a stream)

Week 13 (Apr 13):

- Introduction to aerodynamics
  - Conformal mapping
  - Two-dimensional airfoil theory
  - Finite wing theory, drag due to lift (induced drag)

Week 14 (Apr 20):

- Introduction to turbomachinery
  - Centrifugal pump
  - Mixed and axial flow pumps
  - Pump performance and characteristics
  - Turbines (gas, impulse, reaction, wind)

Week 15 (Apr 27):

- Introduction to biofluid mechanics
  - Blood flow and circulatory system
  - Fluid mechanics of plants

Week 16 (May 02 - May 06): Study Week

Week 17 (May 11): Exam II

MECE E4210 Energy Infrastructure Planning

Professor: Michael Waite
Office Hours: Mondays 1:30-2:30pm
Location: Mudd 134F

Teaching Assistant: Terry Conlon
Office Hours: Tuesdays noon-1:30pm, Fridays noon-1:30pm
Location: MECE TA Room, Mudd 122B

Prerequisites: Programming experience in Python, Matlab or R; concepts of thermodynamics and energy sources; some linear algebra and statistics is ideal

Course Structure: Approximately the first half of the course will consist of (a) lectures on energy systems engineering considerations, with a focus on integration of variable renewable energy (VRE, wind and solar) and (b) developing data-driven computation models to analyze energy infrastructure under such scenarios. Project assignments will reflect these subjects. The second half will introduce thermal loads, energy districts and integrated energy system planning. Much of the student effort will involve a final district design and data-driven modeling project with an intermediate "milestone" assignment.

Assignments: Assignments will primarily be data-driven analysis projects that will require computational/programming models developed in, e.g., Python, Matlab or R. Regular reading assignments will also be assigned. Straightforward quantitative assignments may also be given in the second half of the course intended to assist in the design project.

Final Design Project: More detail will be provided approximately midway through course, but a long-term project will focus on the analysis and design of a grid-connected community energy system / microgrid / energy district in the context of greater penetration of VREs and local growth in demands. Through the "milestone", this will be a structured assignment with the remainder of the project requiring you to present and analyze a design for the community energy system. A final project presentation with feedback from instructors will precede submission of a final report.

Quizzes: Two quizzes, about one hour each, covering readings and lectures.

Grading: Projects 1-3 – 30% (12.5% each)
Quizzes – 25% (12.5% each)
Design project milestone – 12.5%
Final project/report – 17.5%
Final presentation and class participation – 7.5%

Course Schedule and Topics
(May change given guest lecture availability and class/professor interests and schedule)

Date	Lecture Topics	Assignments
1/22	- Course introduction/overview - Building demands and diesel/fossil generators	
1/29	-Solar PV and battery storage - Economic calculations, levelized cost of electricity	
2/5	Grid integration of variable renewable energy (VRE); Challenges and solutions in different regions	**Project 1 due**
2/12	Electricity grid formation; load balancing; central on-demand generation; generator types/roles	
2/19	1st half: Deep renewable penetration scenarios and implications 2nd half: Working session for Project 2	
2/26	Electricity markets; location-based marginal pricing; ancillary services	**Project 2 due**
3/5	**Quiz 1** (First half of class) Lecture: Baseload generation; nuclear and hydro considerations	
3/12	*Spring break week – no class*	
3/19	Flexible generator/hydro operation; grid-connected storage 2nd half: Project 3 review and working session	
3/26	Thermal loads; greenhouse gas emission; space heating equipment; heat pumps vs. fossil fuel boilers/furnaces	**Project 3 due**

4/2	Continuing with thermal loads; district energy demands (base electric, cooling, heating); delivered energy cost components	
4/9	Computing greenhouse gas emissions for different end use equipment and electricity generators; thermal system design and operation effects on energy, costs, emissions; milestone review	
4/16	Campus energy systems; combined heat and power (CHP); integrated district energy solutions	**Final project milestone due**
4/23	Electricity transmission and interconnected energy systems; reliable system operation; energy decarbonization studies	
4/30	**Quiz 2** (First half of class) Second half: In-class consultation/working time on final project	
5/7	**Final project presentations** *5/7 is expected final date*	**Final project report due 5/9**

MECE E4211 **Energy Sources and Conversion**

Prerequisite: ME 3301 THERMODYNAMICS OR Equivalent.

Class	Mondays	4:10 to 6:00pm
	Mondays	Discussion on HW/readings
Occasional guest	Various times	

Recitation/office Friday	TBD	TBD
Additional Office Hours	12-1pm	Monday

9/11/17 Introductory	
	Primary sources of energy Energy and Power, Units Energy carriers, Dispatchable/baseload Fossil Fuels Growth Models Scale, nature of demand, energy carriers
9/18/17	Engines How do engines work? Transportation/power generation Engines (Otto, Diesel, Stirling), Hybrid, PHEV 9/25/17 Deep dive: engines Issues of energy density and power density
10/2/17	vdP work based cycles for power review both rankine and brayton variations
10/9/17	Basics of Turbomachinery, axial flow machine basics
10/16/17	Turbomachines - temperature and pressure
10/23/17	Wind Energy- wind resource
10/30/17	Wind Energy- HAWT basic blade design
6-Nov	No class
13-Nov	Midterm
20-Nov	Power Electronics
27-Nov	Solar resource Solar radiation, geometry, sizing, solar-thermal, CPV, optics
4-Dec	Solar Cells/Modules and Systems
11-Dec	Storage technology overview Decentralized vs centralized options Generation/distribution/transmission Drivers for centralization/decentralization Basics of cost analysis

Course Evaluation Scheme

Homework	10%
class participation	10%
Quiz short	15%
Midterm	25%
Final	40%

Lumley, J. L., ***Engines*** **,** Cambridge, 1999.
Useful Books: (discuss in class)

Fundamentals of Renewable Energy Processes, Aldo DaRosa, Elsevier ***Chemistry of the environment*** by Spiro and Stigliani. Prentice Hall, 2003. Hill and Peterson: ***Mechanics and Thermodynamics of Propulsion*****,** Addison Wesley, 1992**.** William Bathie, Wiley, ***Fundamentals of Gas Turbines*** 1996. Spera, D.A. (Ed.) ***Wind Turbine Technology*** . ASME Press. 1994. Markvart, Tomas, ***Solar Electricity***, John Wiley and Sons, 1994.

MECE 4212 Microelectromechanical Systems

Scheduled meeting time: Weds 4:10-6:40PM

Instructor: Prof. Jim Schuck
Office: Mudd 1009 NWC; Office Hours: Thursday 10:30-11:30PM Email: pjs2191@columbia.edu
Teaching Assistant: Emanuil Yanev
Office: TBD; Office Hours: TBD Email:

Course Materials:
(Required) Practical MEMS, Ville Kaajakari, Small Gear Publishing, 2009 (Recommended) Microsystems Design, Stephen Senturia, Kluwer, Boston, 2001.

Course Objective: To explore the exciting physics and engineering at small – order of micrometers (10^{-6} m) or less – length scales. This covers an appreciation of micro- and nano-fabrication technologies, dynamics and structural mechanics, actuation and detection of motion, and fluids at these length scales. The structure of this course will combine lectures, case studies, a team-level design project, and hands-on laboratory experiences.

Course Description and Bulletin: This is an exciting interdisciplinary course covering the physics, engineering, and design of microsystems, ranging from micro- and nano- fabrication, mechanics, fluid dynamics, electronics and optics with special emphasis on small length scale devices. This subject presents an introduction to micro- and nano-scale devices, using examples from micro- and nano-electromechanical real-world applications. Emphasis of the class will be on the design modeling and simulation of such devices. Lectures during the first half of the term will cover physics and engineering on these length scales: such as mechanics and dynamics, actuation and sensing methods, optics, heat transfer, fluids and device fabrication. During the second half, we will explore specific micro- and nano-scale design projects, and device case studies, with a section where students will get actual hands-on experiences with sample microdevices.

Assignments:
For the **Lecture** portion of the course (~ first seven weeks), each student will be responsible for the material covered in class and reading assignments from the *Practical MEMS* textbook (Kaajakari). Homework's will be assigned weekly and a midterm exam will be held on the eighth week. Collaboration on the homeworks is encouraged. Collaboration is not allowed on the midterm exam.

For the **Design** portion of the course (~ the next seven weeks: mid-Oct to mid-Dec), students will be assigned into groups to pursue a MEMS design project. The design projects will cover state-of-the-art research. A group written report and presentation on the design project will be held at the end of the semester.

In parallel, for the **Laboratory** portion of the course (mid-Oct to mid-Dec), each student will be able to use a set of virtual tools to design/model a widely used MEMS device. Each group of students will then have the opportunity to work with an actual MEMS device for characterization.

Grading: Student grades will be determined from the midterm exam, homework, design project and laboratory characterization scores as follows:

- **Lecture**: Midterm Exam – 30% and Homework – 20%
- **Design**: Design Project (written report and presentation) – 30%
  (20% written report and 10% presentation)
- **Laboratory**: MEMS Characterization – 20%.

Microelectromechanical Systems

MECE 4212 Outline

Week	Lecture topic	Laboratory Activity
1 (9/6/17)	**Introduction, Scaling, MEMS Markets and Applications** (Kaajakari-Chap. 1, Senturi-Chap. 1-2, Device Electronics for Integrated Circuits, Muller Chapter 1-2) **MEMS Materials and Fabrication:** General Concepts Silicon, Semiconductor Physics and Silicon Micromachining (Senturia-Chap. 3)	
2 (9/13/17) 3 (9/20/17)	**MEMS Materials and Fabrication (cont.):** Silicon and Silicon Micromachining (Senturia-Chap. 3) **MEMS Materials and Fabrication (cont.)** **MEMS Mechanics:** a) Statics (Kaajakari-Chap 4; Senturia-8.1-8.4, 9.1-9.6,10.4)	Process simulation: basic lithography, deposition, and etching processes Continuation of week 2 activities

4 (9/27/17)	**MEMS Mechanics:** a) Dynamics (Kaajakari: Chap 12, Appendix B; Senturia: 7.1 - 7.2), Lumped Element (Chap. 5) **MEMS Sensing Mechanisms:** a) Piezoresistive Sensing (Kaajakari: Chap 5; Senturi: 18.2)	Process simulations: integrated process simulation of a pressure sensor
5 (10/4/17)	**Piezoresistive Signal Conditioning:** Operational Amplifiers, (Kaajakari: Chap 8-9) **MEMS Limits of Operation:** Noise (Kaajakari: Chap 2), Dissipation, and Nonlinearity (Kaajakari: Chap 11) **MEMS Sensing Mechanisms:** a) Capacitive Sensing (Kaajakari: Chap 6) **MEMS Actuation:** b) Capacitive Actuation - Electrostatics (Kaajakari Chap. 15)	Continuation of week 4 activities a) Capacitive Sensing (Kaajakari: Chap 6) Piezoelectric Sensing (Kaajakari: Chap 7; Senturia 21.4-21.5)
6 (10/11/17)	**MEMS Sensing Mechanisms:** a) Piezoelectric Sensing (Kaajakari: Chap 7; Senturia 21.4-21.5) **MEMS Actuation:** a)Piezoelectric Actuation (Kaajakari Chap 16) b) Thermal Actuation (Kaajakari Chap 17)	Continuation of week 4 activities
7 (10/18/17)	MEMS Devices: Case Studies of Resonators and/or Gyros FEA Modeling of MEMS - COMSOL **Laboratory Introduction Lecture:** Labs: Pressure Sensor (Piezoresistive) (Kaajakari: Chap 13), Micro-Mirror (Electrostatics), Quartz Resonator (Piezoelectric)	Form groups and define topic for MEMS / NEMS design projects
8 (10/25/17)	**Midterm Exam**	Define specifications for MEMS / NEMS design project
9 (11/1/17)	**DESIGN**: MEMS / NEMS Project	**LABORATORY**: Part 1
10 (11/8/17)	**DESIGN**: MEMS / NEMS Project	**LABORATORY**: Part 2
11 (11/15/17)	**DESIGN**: MEMS / NEMS Project	**LABORATORY**: Part 3
12 (11/29/17)	**DESIGN**: MEMS / NEMS Project	**LABORATORY**: Part 4
13 (12/6/17)	Design Project Group Presentations; Laboratory report due	
14 (12/13/17)	**Final Projects Due**	

References:

Books:

- Kajaakari, Ville. *Practical MEMS.* 2009.
- Senturia, Stephen. *Microsystem Design.* 2001.

Journals:

- Sensors and Actuators A & B (Elsevier).
- IEEE Microelectromechanical Systems (MEMS)

Databases (Best Search Tools, Access through Columbia Library Website)

- Science Direct
- IEEE Xplore http://ieeexplore.ieee.org/Xplore/home.jsp
- Web of Science

Conferences:

- IEEE MEMS, http://www.mems2017.org/
- IEEE Transducers, http://www.transducers2017.org/
- IEEE Eurosensors
- Solid-State Sensors, Actuators and Microsystems Workshop. Hilton Head, NC

Other Resources:

http://www.mems.sandia.gov/ SANDIA National LABS MEMS Projects

https://www.mems-exchange.org/ Microsystems foundry and device Prototyping

http://mail.mems-exchange.org/mailman/listinfo/mems-talk E-list for MEMS folks building devices

www.darpa.mil/mto DARPA/MTO: Follow link under MEMS to see Projects

www.mosis.org The website with user foundries for integrated Circuits

http://www.memscap.com/products/mumps MUMPS process flow Foundry

www.smalltimes.com A trade journal with useful info about MEMS and NEMS

MECE E4213 Bio-Microelectromechanical Systems (BioMEMS): Design, Fabrication and Analysis

MECE E4213 3 Points,
Course Homepage: https://courseworks.columbia.edu/

Lectures: Mondays 4:10 – 6:40 pm 307 Pupin Laboratories

Instructor: Professor Qiao Lin
Office: 236 Mudd
Phone: 4-1906
Email: qlin@columbia.edu
Office hours: TBD

Objectives
This course is intended to introduce students to the emerging field of bio-microelectromechanical systems (BioMEMS), with an emphasis on design, fabrication and analysis aspects. BioMEMS devices and systems hold great promise in a wide range of applications in biology and medicine. Class material will discuss relevant fundamental principles and technologies for BioMEMS. These include various aspects in the design, fabrication, and analysis of BioMEMS.

Outline
Through a combination of lectures, literature research and design projects, the following topics will be broadly covered in the course:

1. Micro- and nanofabrication techniques: silicon micromachining, polymer microfabrication, nanofabrication, and system integration.
2. Fundamentals of microfluidics: hydrodynamic and electrokinetic microfluidic devices
3. Fundamentals of MEMS biosensing and detection: *in vivo* and *in vitro* MEMS sensors, transduction principles, noise analysis, and wireless transmission
4. Biocompatibility and surface modification of MEMS devices
5. Microfluidic devices and systems (e.g., sample preparation, separations, reactions, molecular and cellular manipulation, and drug delivery)
6. Micro and nano-biosensors

Course Mechanics
The course will consist of lectures, a reading project and a design project. There will be no regular homework assignments or exams. However, exercise problems will be handed out when appropriate to enhance understanding of class material.

Lectures. Lectures will cover technology and physical principles that BioMEMS devices and systems are based upon. Emphasis will be placed on using fundamental engineering principles to understand, analyze and design microfluidic devices. Case studies involving detailed modeling, simulation and design of select microfluidic devices will be included.

Reading Project. Students will be divided into teams to research the microfluidic literature. Each team will select a topic with guidance from the instructor and learn and study the topic by reading relevant books and research papers. Each team will be required to submit a report and make a presentation in class. Examples of information that should be covered in the report and presentation include the background and significance of the topic, fundamental concepts and principles, methods and technology, and a review of representative research efforts for the topic selected.

Design Project. Students will, divided into the same teams as for the reading project, perform a design project. Each team will select an application and design a device for the application. Alternatively, in lieu of a device design, the project may involve an in-depth analysis of a chosen device, provided the analysis has not been reported in the literature. Each team will be required to submit a report on their design or analysis.

If the project addresses a design, the report should clearly present the following for the device: (1) background and significance; (2) device concept, design and operating principle; (3) detailed analytical and/or numerical calculations predicting the device performance; (4) fabrication processes including microfabrication techniques needed; and (5) photomask layout if appropriate. If the project addresses an analysis, the report should include a description of the device concept, details of a physical model for the device, solution procedure, and figures that present analysis results and discussions that give insights into the device.

Recommended References

- S.D. Senturia, *Microsystem Design*, Springer, 2000.
- N.-T. Nguyen and S.T. Wereley, *Fundamentals and Applications of Microfluidics*, 2nd edition, Artech House, 2006.

Course Grading and Project Timeline

Final grades will be given based on the reading (50%) and design projects (50%). Exercise problems will not be included in final grading. The grading criteria and tentative schedule for the projects are as follows.

Tentative Date	Reading Project (50 points)	Design Project (50 points)
Monday, 9/16	Team formation	
Monday, 9/30	Reading topic selection: **5-minute, 1-slide PPT presentation** of the selected topic, and the scope of the literature study (5 points)	
Monday, 10/7		Design topic selection: **5-minute, 1 or 2-slide PPT presentation** of the selected topic, and the scope of the design or analysis (5 points)
Monday, 10/21	Reading project outline: **10-minute PPT presentation** on a detailed outline of references to be reviewed (10 points)	
Monday, 10/28		Design project outline: **10-minute PPT presentation** on a detailed project outline (10 points)
Monday, 11/11	Reading project review: complete draft of PPT slides **due** (10 points)	
Mondays, 11/18, 11/25, 12/2	Reading project presentations by individual teams (15 points)	
Monday, 12/2		Design project review: complete draft of PPT slides **due** (10 points)
Monday, 12/9		Design project presentations by individual teams (15 points)
Monday, 12/16	Reading project report and PPT slides **due** (10 points)	Design project report and PPT slides **due** (10 points)

Percentage grades will be converted into letter grades based on the following chart:

90 or above:	A
80 or above (below 90):	B
70 or above (below 80):	C
60 or above (below 70):	D
59 or less:	R

MECE E4302: Advanced Thermodynamics (Spring 2020)

Time: Thursday 4:10 pm-6:40 pm

Place: 644 Mudd Building

Instructor:
Prof. Michael P. Burke
Email: mpburke@columbia.edu
Office Hours: Friday 2:00-3:00 pm
Office Hours Location: Mechanical Engineering Conference Room

Grader/Course Assistant:
TBD
Email: TBD

Required Textbook:
C. Borgnakke, R.E. Sonntag, *Fundamentals of Thermodynamics*, 8th Ed., 2013.[1]
[1]on course reserve: NW Corner Building Library

Other Useful Textbooks:
M.J. Moran, H.N. Shapiro, *Fundamentals of Engineering Thermodynamics*, 6th Ed., 2008.[1]
C. Kittel, H. Kroemer, *Thermal Physics*, 2nd Ed., 1980.[1]
S.R. Turns, *Introduction to Combustion: Concepts and Applications*, 3rd Ed., 2011.[1]
C.K. Law, *Combustion Physics*, Cambridge University Press, 2006.[2]

[1] on course reserve: NW Corner Building Library
[2] on course reserve: e-reserve

Course Description:
Advanced classical thermodynamics: exergy, Maxwell relations, equations of state and properties for ideal and non-ideal gases, generalized behavior, mixtures and solutions, phase and chemical behavior, combustion, compressible flow, applications to power generation and refrigeration systems.

Course Prerequisites:
Introductory thermodynamics at the undergraduate level or instructor's permission.

Course Objectives:
After completion of the course, the students will be able to
1. Demonstrate a firm understanding of core thermodynamic concepts and foundations. 2. Perform thermodynamic analyses (energy, entropy, exergy, etc.) of complex, integrated thermodynamic systems. 3. Be comfortable with and effectively utilize thermodynamic relations for various substances. 4. Calculate heat release, final temperatures, and equilibrium composition of final products in reactive systems. 5. Apply knowledge and concepts to various application domains (power systems, refrigeration systems, etc.)

Attendance Policy:
Students are expected to attend all lectures and to come prepared. Students are responsible for any material covered during absences.

Grading Policies:
30% Homework 35% Midterm examination 35% Final Examination

Midterm exam date:
Thursday, March 12 in class

Final exam date:
Finals period at official time scheduled by registrar

Homework Policies:
You may work together on homework sets while exploring and discussing general concepts and methods, but all work you submit must be completed and written up by yourself individually and must represent your level of knowledge and understanding of the subject.

Academic Honesty Policies:
The academic honesty policies for the Mechanical Engineering Department are listed at:
http://me.columbia.edu/academic-honor-code
The Policy on Conduct and Discipline that applies to all endeavors at the School of Engineering and Applied Science (SEAS) is described at:
http://bulletin.engineering.columbia.edu/policy-conduct-and-discipline
In addition, Columbia College has an extensive website devoted to Dishonesty in Academic Work at
http://www.college.columbia.edu/academics/academicdishonesty
Especially relevant for the writing of reports is the discussion of plagiarism and how to avoid it by proper acknowledgement of sources, as discussed in detail at:
http://www.college.columbia.edu/academics/dishonesty-plagiarism

Under no circumstances is it acceptable to copy text from another source without proper acknowledgment.
It is the responsibility of each student to read and understand these policies.

Furthermore, in this course the follow constitutes cheating:
• Copying assignments from others.
• Providing and/or consulting solutions sets from previous years.
• Consulting exams from previous years that were not made available by instructor.
• Completing individual assignments in a group, when permission not explicitly granted by instructor.
• Plagiarizing the work of others.

Cheating may lead to the following consequences:
• Student receives a failing grade for a specific assignment.
• Student receives a failing grade for an entire course.
• Student may be expelled from the university.

Student rights:
• Academic honesty policies clearly explained at start of semester
• Course requirement and grading policies must be clearly stated at start of semester.
• Textbook and reference book usage must be clarified at start of semester.
• Homework assignments, midterm exams, and final exams will be graded in a timely manner.
• Instructor and teaching assistants must provide office hours or otherwise explain procedure for meeting with students.
• Instructors will provide pertinent information on assignments in a timely manner.

Tentative schedule

Class #	**Date**	**Topic**
1	Jan. 23	Introduction, Definitions, and Foundations
2	Jan. 30	Foundations
3	Feb. 6	Foundations
4	Feb. 13	Exergy
5	Feb. 20	Thermodynamic relations
6	Feb. 27	Thermodynamic relations
7	Mar. 5	Mixtures
8	Mar. 12	MIDTERM EXAMINATION
9	Mar. 19	NO CLASS – SPRING RECESS
10	Mar. 26	Mixtures
11	Apr. 2	Chemical reactions
12	Apr. 9	Chemical reactions
13	Apr. 16	Chemical and phase equilibria
14	Apr. 23	Chemical and phase equilibria
15	Apr. 30	Compressible flow basics
16	May 7	NO CLASS – STUDY DAYS
17	Finals period	FINAL EXAMINATION

MECE E4305: Mechanics and Thermodynamics of Propulsion

Course Description
This course introduces the basic principles of propulsion, including a review of the mechanics and thermodynamics of fluid flow. Thermodynamic cycle and component analysis of air-breathing propulsion systems, including turbojet, turbofan, turboprop, and ramjet engines are covered. Elementary rocket performance principles are introduced.

Classes: Saturday, 9:40am-12:00pm in Seeley W. Mudd 627
Lecturer: Professor Sean Bradshaw (sb3964@columbia.edu)
Email: sb3964@columbia.edu
Bio: http://me.columbia.edu/sean-bradshaw-0
Course Assistant: Elon Gordon
Email: eg2876@columbia.edu

Prerequisites: Thermodynamics MECE E3301, Heat Transfer MECE E3311, Turbomachinery MECE E4304 (or instructor approval)

Grading:
Your class grade will be based a mid-term exam and a final term project.
Mid-Term Exam: 50% Final Term Project: 50%

Term Project: The final term project, which consists of 50% of your class grade, will be due on the last day of class, April 28, 2018. The final term project consists of two components: a written report and an MS PowerPoint presentation.

Textbooks:
1. "Aircraft Engines and Gas Turbines", J. Kerrbrock, MIT Press, 1992.
2. "Mechanics and Thermodynamics of Propulsion", P. Hill and C. Peterson, Addison-Wesley, 1992.

Lecture Schedule, Topics, and Reading Material

Lecture #	Lecture Topic	Reading Material	Date
1	Introduction to Aircraft Propulsion	"Aircraft Engines and Gas Turbines," Chap. 1	20-Jan
2	Mechanics & Thermodynamics of Fluid Flow	"Aircraft Engines and Gas Turbines," Chap. 1	27-Jan
3	Propulsion Systems Analysis	"Aircraft Engines and Gas Turbines," Chap. 11	3-Feb
4	Ideal Cycle Analysis	"Aircraft Engines and Gas Turbines," Chap. 2	10-Feb
5	Non-Ideal Cycle Analysis	"Aircraft Engines and Gas Turbines," Chap. 3	17-Feb
6	Turbomachinery	"Aircraft Engines and Gas Turbines," Chap. 5,6	24-Feb
	Mid-Term Exam		3-Mar
7	Combustion Systems	"Aircraft Engines and Gas Turbines," Chap. 4	10-Mar
	No Class/Spring Break		17-Mar
8	Introduction to Rocket Propulsion	"Mechanics & Thermodynamics of Propulsion," Chap. 10	24-Mar
9	Rocket Performance	"Mechanics & Thermodynamics of Propulsion," Chap. 10	31-Mar
10	Rocket Nozzle Aerodynamics & Heat Transfer	"Mechanics & Thermodynamics of Propulsion," Chap. 11	7-Apr
11	Rocket Nozzle Aerodynamics & Heat Transfer	"Mechanics & Thermodynamics of Propulsion," Chap. 11	14-Apr
12	Guest Lecture: Exhaust Systems Aerodynamics		21-Apr

	Final Term Projects Due		28-Apr

Modern Commercial Jet Engines

General Electric Aircraft Engines:

LEAP Engine
https://www.cfmaeroengines.com/engines/leap/

CF34 Engine
https://www.geaviation.com/commercial/engines/cf34-engine

GE90 Engine
https://www.geaviation.com/commercial/engines/ge90-engine

Pratt & Whitney Aircraft Engines:

PW1000G Geared Turbofan Engines
http://www.pw.utc.com/PurePowerPW1000G_Engine

V2500 Turbofan Engine
http://www.pw.utc.com/V2500_Engine

PW4000 Engine
http://www.pw.utc.com/PW4000112_Engine

Rolls Royce:

Trent 7000
https://www.rolls-royce.com/products-and-services/civil-aerospace/airlines/trent- 7000.aspx#/

Trent XWB
https://www.rolls-royce.com/products-and-services/civil-aerospace/airlines/trent- xwb.aspx#/

RB211
https://www.rolls-royce.com/products-and-services/civil-aerospace/airlines/rb211-535e4.aspx#overview

Course Material - Outline

- Aerodynamic variables
- Dimensional Analysis (force coefficients, Reynolds Number, etc.)
- Flow Types
- Vector Calculus
- Control Volumes and Fluid Elements
- Continuity Equation Development
- Momentum Equation Development
- Energy Equation Development
- Substantial Derivative
- Vorticity
- Circulation
- Stream Function
- Bernoulli's Equation
- Wind Tunnel Applications
- Different Flow Types: uniform, source, doublet, vortex.
- Airfoil Characteristics
- The Kutta-Joukowski Theorem
- Kelvin's Circulation Theorem
- Thin Airfoil Theory (Symmetric Airfoil)
- Airfoil Drag
- Viscous Flow and Drag
- Downwash
- Biot-Savart Law
- Lifting Line Theory
- Normal Shock Wave
- Oblique Shock Wave
- Flow through Nozzles
- Inflight Icing
- Introduction to Flight Performance
- Introduction to Stability & Control

MECE E4312 Solar Thermal Engineering

Mondays 7:00-9:30PM
Instructors: Mohammad H. Naraghi

Course Description: Fundamentals of solar energy transport: radiation heat transfer, convention, conduction and phase change processes. Heat exchangers and solar collectors: basic methods of thermal design, flow arrangements, effects of variable conditions, rating procedures. Solar energy concentration. Piping Systems: series and parallel arrangements, fluid movers. Thermal response and management of photovoltaic energy conversion. Solar energy storage. Solar cooling, solar thermal power and cogeneration. Applications to the design of solar thermal engineering systems.

Text: No textbook is required; class notes will be posted on the coursework site

Recommended Reference: SOLAR ENGINEERING OF THERMAL PROCESSES - Fourth Edition, 2013, by Duffie and Beckman

http://www.powerfromthesun.net/book.html

Topics Covered: **Topics**
- Solar Radiation, extraterrestrial radiation, definitions, solar and standard times................
- Solar angles, altitude and azimuth angles, seasonal variation of solar angles.................
- Solar beam angles with respect to surface, shading, geometric factor........................
- Available solar radiation, methods of calculation solar irradiance on a surface ....
- Clear sky and clearness index methods for calculating irradiance on a surface.........
- Heat transfer topics related to solar energy, radiation and convection heat transfer topics
- Radiation properties of opaque material..
- Solar radiation transmission through glazing, transmittance-absorptance product..........
- Flat plate solar collectors...
- Concentrating solar collector ....
- Thermal energy storage ....
- Solar system thermal calculations...
- Photovoltaic systems...

Assessment Tools:

Midterm exam	20%
Final Exam	40%
Projects and homework	40%

OFFICE HOURS: M 6:00PM-7:00PM
CONTACT INFORMATION: Email: mhn22@columbia.edu

MECE E4314 Energy Dynamics of Green Buildings

1. **Credits:** 3 Credit hours
2. **Contact Hours:** Click here to enter text
3. **Instructor:** Mohammad H. Naraghi, Ph.D
4. **Textbook Information:**
   "Energy Dynamics of Green Buildings," Naraghi, 2009 M., Linus Learning, ISBN 13: 978-1-60797-780-3, ISBN 10: 1-60797-780 https://linuslearning.com/product/energy-dynamics-green-buildings/
   a. **Other Supplemental Materials:** None

5. **Specific Course Information**
   a. **Course Description:** Environmental Technologies – A review of environmental technologies historically used in buildings to achieve human comfort will serve as an introduction to the objectives for the course. There will be a review of the fundamental physics that effect internal and external environmental conditions. Site and climate analysis will be the starting point for defining performance criteria of the built environment. Students will be introduced to analysis tools for interpreting weather data and the fundamentals of occupant comfort. Criteria used to define internal environmental conditions will be discussed as a design goal to which all building elements must strive to achieve through systems integration. Students will be challenged to engage the making of building systems through a design process that understands systems as complete assemblies with designed relationships to other systems (manmade and natural/internal and external). The content of the course will emphasis the tectonic aspects of architecture; however other aspects such as the technology and methods for maintaining comfort conditions and ecological balance within buildings will be reviewed with an emphasis on high performance sustainable design, human comfort, social responsibility, ecology, and sustainability.
   b. **Prerequisites:** None
   c. **Co-requisites:** None
   d. **Course Required or Elective:** Elective Course

6. **Specific Goals for the Course**
   a. Specific Outcomes of Instruction: The course emphasizes understanding the impact that various environmental systems have on the building design and operation process
   b. Student Outcomes Addressed by Course: None

7. **Brief list of topics to be covered**
   Indoor air quality comfort and health
   High Performance Building Considerations/Building Energy Use and Atmosphere
   Passive and active use of solar energy in buildings
   Water use, distribution and management
   Air distribution system
   Cooling and heating load calculations
   Semester-long project

MECE E4320: Introduction to Combustion

Time: Thursday 4:10 - 6:40 p.m.

Place: 253 Engineering Terrace

Instructor: Prof. Michael P. Burke
Email: mpburke@columbia.edu
Office Hours: Friday 2:00-3:00 p.m.
Office Hours Location: Mechanical Engineering conference room

Teaching Assistant: Mark Barbet
Email: mcb2261@columbia.edu
Office Hours: Tuesday 2:00 p.m.
Office Hours Location: Mechanical Engineering TA room (Mudd 122B)

Required Textbook:
C.K. Law, *Combustion Physics*, Cambridge University Press, 2006.[1]

[1] on course reserve: e-reserve

Other Recommended Textbooks:

S.R. Turns, *Introduction to Combustion: Concepts and Applications*, 3rd Ed., 2011.[2]
C. Borgnakke, R.E. Sonntag, *Fundamentals of Thermodynamics*, 8th Ed., 2013.[2]
M.J. Moran, H.N. Shapiro, *Fundamentals of Engineering Thermodynamics*, 6th Ed., 2008.[2]
M.J. Pilling, P.W. Seakins, Oxford University Press, *Reaction Kinetics*, 1995.[1]
J.B. Heywood, *Internal Combustion Engine Fundamentals*, 1988.[2]
C. Kittel, H. Kroemer, *Thermal Physics*, 2nd Ed., 1980.[2]

[1] on course reserve: e-reserve
[2] on course reserve: NW Corner Building Library

Course Description:
Thermodynamics and kinetics of reacting flows; chemical kinetic mechanisms for fuel oxidation and pollutant formation; transport phenomena; conservation equations for reacting flows; laminar non-premixed flames; laminar premixed flames; flame stabilization, quenching, ignition, extinction, and other limit phenomena; flame aerodynamics and turbulent flames; detonations.

Course Prerequisites:
Introductory thermodynamics, fluid mechanics, and heat transfer at the undergraduate level or instructor's permission

Course Objectives:
After completion of the course, the students will be able to

1. Calculate heat release during combustion, final temperatures, and composition of Final products.
2. Perform chemical kinetic analyses and describe key features of fuel oxidation and pollutant formation chemistry.
3. Describe controlling processes in flames and determine how flame characteristics depend on the chemical and physical properties of the fuel and thermofluidic conditions.
4. Explain (and in some cases estimate) key aspects of flame stabilization, flame quenching, ignition, extinction, and other limit phenomena.
5. Understand the assumptions/limitations of the equations derived in class and apply conservation laws to derive new solutions to chemically reacting flow systems.

Attendance Policy:
Students are expected to attend all lectures and to come prepared. Students are responsible for any material covered during absences.

Homework Policies:

You may work together on homework sets while exploring and discussing general concepts and methods, but all work you submit must be completed and written up by yourself individually and must represent your level of knowledge and understanding of the subject.

Grading Policies:

30%	Homework
35%	Midterm examination
35%	Final Examination

Academic Honesty Policies:

The academic honesty policies for the Mechanical Engineering Department are listed at:
http://me.columbia.edu/academic-honor-code
The Policy on Conduct and Discipline that applies to all endeavors at the School of Engineering and Applied Science (SEAS) is described at:
http://bulletin.engineering.columbia.edu/policy-conduct-and-discipline
In addition, Columbia College has an extensive website devoted to Dishonesty in Academic Work at
http://www.college.columbia.edu/academics/academicdishonesty
Especially relevant for the writing of reports is the discussion of plagiarism and how to avoid it by proper acknowledgement of sources, as discussed in detail at:
http://www.college.columbia.edu/academics/dishonesty-plagiarism
Under no circumstances is it acceptable to copy text from another source without proper acknowledgment.

It is the responsibility of each student to read and understand these policies.

Furthermore, in this course the follow constitutes cheating:

- Copying assignments from others.
- Providing and/or consulting solutions sets from previous years.
- Consulting exams from previous years that were not made available by instructor.
- Completing individual assignments in a group, when permission not explicitly granted by instructor.
- Plagiarizing the work of others.

Cheating may lead to the following consequences:

- Student receives a failing grade for a specific assignment.
- Student receives a failing grade for an entire course.
- Student may be expelled from the university.

Student rights:

- Academic honesty policies clearly explained at start of semester
- Course requirement and grading policies must be clearly stated at start of semester.
- Textbook and reference book usage must be clarified at start of semester.
- Homework assignments, midterm exams, and final exams will be graded in a timely manner.
- Instructor and teaching assistants must provide office hours or otherwise explain procedure for meeting with students.
- Instructors will provide pertinent information on assignments in a timely manner.

Tentative Schedule:

Class #	**Date**	**Topic**
1	Sep. 7	Introduction, Thermodynamics Review, Stoichiometry, Heat Release
2	Sep. 14	Chemical Thermodynamics and Equilibrium I
3	Sep. 21	Chemical Thermodynamics and Equilibrium II
4	Sep. 28	Reaction Kinetics
5	Oct. 5	Combustion Kinetic Mechanisms
6	Oct. 12	Conservation Equations
7	Oct. 19	MIDTERM EXAMINATION
8	Oct. 26	Laminar Non-Premixed Flames I
9	Nov. 2	Laminar Non-Premixed Flames II
10	Nov. 9	Laminar Premixed Flames I
11	Nov. 16	Laminar Premixed Flames II
12	Nov. 23	NO CLASS – THANKSGIVING
13	Nov. 30	Flame Stabilization/Aerodynamics, Limit Phenomena
14	Dec. 7	Detonations
15	Finals period	FINAL EXAMINATION

MECE E4330: Thermofluid Systems Design

Course Description
Theoretical and practical considerations, and design principles, for modern thermofluid systems. Emphasis on applications of thermodynamics, fluid mechanics, and heat transfer to modeling actual physical systems. Topics include conduction, convection, and radiation heat transfer; boiling, condensation, and phase change heat transfer; multimodal heat transfer, heat exchanger design, and thermal transport systems modeling. Term project on conceptual design and presentation of a thermofluid system that meets specified criteria.

Classes: Saturday, 9:30am-12:00pm in Room 644, Mudd Building
Lecturer: Professor Sean Bradshaw (sb3964@columbia.edu)

Prerequisites: MECE E3100, E3301, E3311
Office Hours: By Appointment

Exams, Term Project, and Grading
The course grade will be based on two exams (33% each) and one final term project (34%).

Exam Dates:
There will be two in-class mid-term exams. Each exam is worth 33% of your final grade. The exams will be open notes and open book. Collaboration will not be allowed during these exams.

Exam I: 10/7/2017

Exam II: 11/11/2017

Term Project:
The term project will consist of a conceptual design and presentation of a thermal-fluids system that meets specified design criteria. The term project final presentations and written reports will be due on December 16, 2017. The presentations and final report be may completed individually or in teams consisting of 2-3 members.

Final Reports Due: 12/16/2017

Presentation Date: 12/16/2017

Textbook: "Fundamentals of Heat and Mass Transfer", F. Incropera, D. DeWitt, 8th Edition

Homework/Classwork Assignments:
Homework and classwork problems will be assigned during the course to aid the learning process. Although these assignments are optional and will not be collected, you are strongly encouraged to attempt these problems to prepare for the exams and the final term project. You are also encouraged to work collaboratively to complete the homework and classwork assignments.

Lecture Schedule, Topics, and Reading Material

Lecture #	Lecture Topic	Reading Material	Date
1	Fundamental Modes of Heat Transfer	Incropera, Chapter 1	9-Sep
2	Multimodal Heat Transfer Analysis	Incropera, Chapter 2	16-Sep
3	Conduction: Steady-State	Incropera, Chapters 3, 4	23-Sep
4	Conduction: Transient	Incropera, Chapter 5	30-Sep
	Exam I		**7-Oct**
5	Convection Fundamentals	Incropera, Chapter 6	14-Oct
6	Forced Convection	Incropera, Chapters 7, 8	21-Oct
7	Free Convection	Incropera, Chapter 9	28-Oct
8	Boiling & Condensation	Incropera, Chapter 10	4-Nov
	Exam II		**11-Nov**
9	Heat Exchangers Term Project Kick-Off	Incropera, Chapter 11	18-Nov
	Thanksgiving Break		25-Nov
10	Radiative Heat Transfer	Incropera, Chapter 12	2-Dec
11	Radiative Heat Transfer	Incropera, Chapter 13	9-Dec
	Term Project Presentations & Reports Due		**16-Dec**

MECE E4430: Automotive Dynamics

Course Description

Prerequisites: ENME 3105; recommended: ENME 3100, 3106. "This course reviews the fundamentals of vehicle dynamics. A systems-based engineering approach is used to explore the following areas: tire characteristics, aerodynamics, stability and control, wheel loads, ride and roll rates, suspension geometry, and dampers. A high-performance vehicle (racecar) platform will be used as an example throughout the course to review these topics.

Course Texts

Required:

- "Race Car Vehicle Dynamics," Milliken and Milliken (RCVD)

Supplemental:

- "Fundamentals of Vehicle Dynamics," Thomas Gillespie;
- Sustainable Energy – without the hot air, David MacKay, 2009,
  - https://www.withouthotair.com/download.html (Links to an external site.)

Recommended:

- Other articles and texts throughout the semester as appropriate

Grading

- Pop quizzes based on lecture materials, general engineering knowledge, and weekly readings – 25%
- Homework – 20%
- Mid-term & Final – 30%
- Final paper / project – 25%

Course Schedule - Wednesdays, 4:10 PM - 6:40 PM

Lecture #1, Sept 5: Introduction

Lecture #2, Sept 12: Lateral load transfer distribution

Lecture #3, Sept 19: Springs and Anti-Roll Bars, Ride rates, roll rates, motion ratios, roll stiffness calculation

Lecture #4, Sept 26: Suspension geometry I

Lecture #5, Oct 3: Applied example w/tire data

Lecture #6, Oct 10: Continue worked example, Damping calculations, shock absorbers

EXAM: Oct 17: Midterm

Lecture #7, Oct 24: Project updates, Vehicle system and damper data analysis

Lecture #8, Oct 31: Data acquisition & analysis

Lecture #9, Nov 7: Intro. to steady state stability and control (i.e. 'handling')

Guest Lecture, Nov 14: Guest Lecture Dr. Edward Kasprzak - Tires, tire testing, tire modeling

Lecture #10, Nov 28: Stability derivatives, compliance, Guest Lecture Chris Woodward -Toyota Racing Development - CFD

Lecture #11: Dec 5: Final Exam & project updates (preliminary results)

Project report due Dec. 22 by midnight (last day of finals)

MECE 4431 Space Vehicle Dynamics

1. Credits: **3 Credit Hours**
2. Contact Hours: Monday 2:10-3:00, Tuesday 4:10–5:00
3. Instructor: Professor Richard Longman

4. Textbook Information: None

a. Other Supplemental Material

Writeups supplied as handouts on many topics in the course

b. List of Reference Books:

Peter C. Hughes, Spacecraft Attitude Dynamics, J. Wiley, 1986 (2004 edition, Dover publications, Mineola, New York) S.W. McCuskey, Introduction to Celestial Mechanics, Addison-Wesley, 1963 John E. Prussing, Bruce A. Conway, Orbital Mechanics, New York: Oxford University Press, 1993
Marshall Kaplan, Modern Spacecraft Dynamics and Control, Wiley, 1976
Bong Wie, Space Vehicle Dynamics and Control
(AIAA Education Series), AIAA (American Institute of Aeronautics & Ast.), 1998 Hanspeter Schaub, John L. Junkins, Analytical Mechanics of Space Systems (AIAA Education Series), AIAA, 2003
Thomas Kane, Peter W. Likins, David A. Levinson, Spacecraft Dynamics,
McGraw-Hill Company, 1983

5. Specific Course Information

a. **Course Description:** Space vehicle dynamics, rocket equations, satellite orbits, initial trajectory designs from earth to other planets, satellite attitude dynamics, gravity gradient stabilization of satellites, spin-stabilized satellites, dual-spin satellites, satellite attitude control, modeling, dynamics, and control of large flexible spacecraft.

b. **Prerequisites:** MECE E3105 or ENME E3105 and ENME E4202 ENME E4202 recommended

c. Co-requisites: None

d. Course Required or Elective: Elective Course

6. Specific Goals for the Course

a. **Specific Outcomes of Instruction:** Satellite orbits, transfer orbits, patched conics, kinematics and dynamics of rigid satellite rotational motion

b. Student Outcomes Addressed by Course: This course addresses the following student outcomes; a, c, k, l and m,

7. Brief List of topics covered:

Overview of course topics
Projectiles. Rocket equation.
Coordinate transformations.
Direction cosine matrices.
Euler Angles.
Spherical triangles.
Great circle.
Kepler's laws.
Derivatives of vectors.
Differential equation of orbits.
Parabolas, hyperbolas, elliptical orbits.
More orbits.
Orbital parameters.
Transfer orbits.
Angular velocity.
Rendezvous equations.
Attitude motion of spacecraft.
Sensors and actuators.
Angular momentum.
Angular momentum equation.
Dyadics.
Inertia matrix.
Euler's equations.
Momentum and energy ellipsoids.
Kinetic energy of rigid body.

Kinematics of rotations.
Equations of rotational motion with kinematic equation choices.
Numerical solution of ode's.
Gravity gradient attitude stabilization, flexible spacecraft, grand tour.

MECE-E4440: Optimization of Dynamic Systems

Summary of the course: Fundamentals for optimizing performance of dynamic systems described by a set of ordinary differential equations based on the theory of variational calculus. Systematic methods to solve the optimization problems using numerical methods. Topics covered include: Static Optimization of systems with equality and inequality constraints, Numerical Methods to solve static optimization problems, Theory of calculus of variations, Application of calculus of variations to solve dynamic optimization problems with equality and inequality constraints, Direct and indirect numerical methods to solve dynamic optimization problems, Finite-time linear systems, Steady state linear systems, Multi degree-of-freedom robotic systems.

Prerequisites: Course on linear and/or nonlinear control theory, Introduction to Robotics, or Permission of the instructor

Notes: The course was taught as an experimental class in Fall 2019.
Time: Tuesday 4:10 pm - 6:40 pm,
Venue: Mudd Building 627
Instructor: Sunil K. Agrawal, Ph.D.
Professor of Mechanical Engg./Rehabilitation and Regenerative Medicine Office: 230 Mudd Hall
Email: Sunil.Agrawal@Columbia.edu

Textbook:

Optimization of Dynamic Systems, Authors: Sunil K. Agrawal and Brian C. Fabien, Kluwer Academic Publishers, ISBN 0-7923-5681-0

Prerequisites: MECEE 4602 or Instructor's Permission

Schedule:

9/03	Chapter 1: Static Optimization
9/10	Chapters 1 Contd. and Chapter 2: Numerical Methods
9/17	Chapter 2 Contd. - Numerical Methods
9/24	Chapter 3: Calculus of Variations
10/1	Chapter 4: Dynamic Optimization
10/8	Chapter 4 Contd. - Dynamic Optimization
10/15	Chapter 5: Dynamic Optimization – Direct Solution
10/22	**Mid-Term Project Report Due**
10/29	Chapter 6: Dynamic Optimization – Indirect Solution
11/5	University Holiday
11/12	Chapter 7: Finite time linear Systems
11/19	Chapter 8: Steady State Linear Systems
11/26	Chapter 9: Multi-degree-of-Freedom Systems
12/3	**Final Project Presentation**

Grading:

Homework:	20%
Mid-Term Project:	30%
(Includes presentation/Technical report)	
Final Project	50%
(Includes presentation/Technical report)	

Other Course Details:

(i) **Homework** will be assigned after the completion of a topic. These will be due in a week after the assigned date. The problems will require programing, simulation, and animation using MATLAB.

(ii) **Mid-Term Project**: The students will work in assigned groups of 2. Define a single- degree-of-system that you will like to optimize the performance. Motivate this system from a practical application. Please discuss your project with the Instructor/TA.
Prepare 6 Powerpoint slides that include the following: Problem statement, Your solution approach, Results, Conclusions and Future Extensions. Write a 3-page technical report in word (2 column 10 point) using the typical format of an IEEE paper (you can use the template of ICRA paper).

(iii) **Final Project**: The students will work in self-selected groups of 2. Define a two or more degree-of-freedom system that you will like to optimize using the principles that you have studied in this course. Motivate this system from a practical application. Please discuss your project with the Instructor/TA.
Presentation - Prepare 6 PowerPoint slides that include the following: Problem statement, Your solution approach, Results, Conclusions and Future Extensions. *Technical Paper* - Write a 3-page technical report in word (2 column 10 point) using the typical format of an IEEE paper (you can use the template of ICRA paper).

(iv) **Course Ethics**: Discussion of the lecture material among students is encouraged. However, home-works must be performed individually.

MECE-E4520 DATA SCIENCE F OR MECHANICAL SYSTEMS

Class format: A series of guest lectures (14 total), Homework, Final Project/Paper

Textbook: None; topic readings assigned for each lecture

Bulletin Description: Introduction to the practical application of data science, machine learning, and artificial intelligence. A review of relevant Python tools necessary for applying data science is reviewed, as well as a detailed review of data infrastructure and database construction for data science. A series of detailed industry case studies from experts in the field of data science will be presented.

Rationale: Data science curriculum generally maintains a strong focus on machine learning, and more broadly, AI fundamentals. A gap exists between academia and the practical application of data science methods in industry. Beyond machine learning and AI in general, a strong basis in Python and a nuanced understanding of the challenges of building appropriate data pipeline and database architecture are foundational requirements for building successful data science programs. This course aims to fill this gap.

Full Description: This seminar-based course will consist of case studies in the field of data science. The course is primarily aimed at engineering students with an interest in data science. The goal of this course is to provide an initial look at a broad range of 'real world' data science applications. Each lecture will provide a background review of current data science methods, followed by an applied example based on current projects at Rho AI. The case studies will generally focus on engineering problems across the waste, water, and energy industries. In addition to AI and machine learning, this class will review data infrastructure and more generally, "DevOps," as a critical component to successful deployment of AI-based solutions.

Grading and requirements: Overall grades calculated as follows: 20% class participation, 30% homework, 50% final project. Attendance is mandatory, as class participation is a critical element of the curriculum (1 letter grade penalty per unexcused absence). Students will be expected to arrive for each lecture on time and participate in the discussion. Readings will mostly consist of relevant industry and research papers relating to practical data science applications for mechanical systems. Readings will be assigned prior to the week's lecture and students will be expected to come to class prepared to discuss assigned readings in the context of that day's lecture material. Homework will be assigned throughout the semester and the penalty for late homework will 10% of the total grade for that assignment per day late. Each student will be required to complete a final project that is based on the class material, but that takes the class material beyond its introductory stage and reports on a recent application of data science for industrial and/or mechanical system processes. Projects can be completed individually or in groups of 2-3, and an idea must be formulated early on in the semester in coordination with the instructor(s).

Lecture #1 (1/22/20) - Introduction to data science, machine learning, and Artificial Intelligence

• Lecture Goal: Understand what machine learning, data science and artificial intelligence are, how they relate to topics you might be familiar with, how they are being applied.

- o What is machine learning?
- o How can you understand it based on current coursework?
- o Techniques / overview
- o Why do we care / why is it hot

• Required reading: selected overviews of key introductory articles and chapters regarding the role of AI and Machine Learning as being applied to business today.

• Homework: run a complete machine learning example focused on the Boston Housing data set. Preliminary analytical approaches will be provided, and students will be encouraged to expand upon these tools to increase the accuracy of the prediction method.

Lecture #2 (1/29/20) – Python 101

• Lecture Goal: Review the foundations of Python programming within the context of data science

• Required reading and other prep:

- o Download Miniconda (version 3+, accept default options): https://conda.io/miniconda.html (Links to an external site.)
- o Download a text editor (e.g. Sublime Text, Atom)
- o Download git: https://git-scm.com/downloads (Links to an external site.)
- o Read A Whirlwind Tour of Python (https://github.com/jakevdp/WhirlwindTourOfPython (Links to an external site.)): Sections 3-5, 7-10, 13, 15

• Lecture Flow:

- o Why use Python?
- o Different ways to interact with Python
- o Write simple scripts using common data science tools

• Homework: TBD

Lecture #3 (2/5/20) - Databases, databases, and databases

• Lecture Goal: provide an appreciation for the wide array of available database "makes and models", along with why their relative strengths/weaknesses are critical to understand in the world of data science.

• Required reading: selected overviews of key database classes (specifically, the difference between relational and non-relational) and commonly used databases in each category (e.g. MySQL/Postgresql, Redis, Elasticsearch, Arango)

• Lecture Flow:
  - o High level overview of relational databases.
    - ▪ Describe the core concepts of tables, normalization, etc.
    - ▪ Describe the SQL query language
    - ▪ Show different examples of relational database options such as MySQL, Postgresql, etc.
  - o Overview of non-relational databases
    - ▪ Describe core concepts, which are far more varied than relational
    - ▪ Show examples of different query languages for databases
    - ▪ Show two examples of non-relational databases (e.g. elasticsearch and arango)

o Real-world example/demonstration
  - ▪ Pit Rho using Postgres for core relational models and Redis for high speed caching during real-time events

o Interactive example of the steps involved in the database selection process
  - ▪ Provide a use case example
  - ▪ Walk through selection process with students, showing techniques for w eighing pros/cons of different options.

o Homework: design a system with the most efficient use of databases based on a provided scenario.

o References / reading materials:
  - ▪ https://github.com/dhamaniasad/awesome-postgres#readme (Links to an external site.)
  - ▪ https://github.com/sindresorhus/awesome#back-end-development (Links to an external site.)

Lecture #4 (2/12/20) - Data Pipelines for ML

• Lecture Goal: provide an understanding on how to collect, move and analyze data for ML.

• Lecture flow:
  - o Overview of methodologies for collecting data (open data vs. proprietary data)
  - o Overview of data ingestion pipelines:
    - ▪ Ingesting, little, but specialized data
    - ▪ Ingesting big data
    - ▪ Ingesting time-series data
    - ▪ Real-time vs batch processing
  - o Overview of tools for data analysis and manipulation:
    - ▪ Jupyter notebooks
    - ▪ Data scaling and transformation
    - ▪ Plotting for visual analysis
  - o Homework:
    - ▪ Pick a real-world problem and design data ingestion pipeline for it

Lecture #5 (2/19/20) - Introduction to Neural Networks and Deep Learning

Class Description:

• Lecture goal: Introduce the neural network, survey the landscape of specialized architectures and their respective fields of applicability and open the discussion of 'deepness' and why these algorithms have been so successful.

• SWBAT: Describe a deep neural network as a series of concepts, highlighting the hierarchical nature of the algorithm.

• Lecture flow:
  - o Expose students' perception of neural networks/deep learning
  - o Early applications & Successes of deep learning
  - o Fundamentals towards a basic neural network
    - ▪ Nonlinearity, logistic regressions, and layering
  - o Neural network
    - ▪ Stitching together logistic units
    - ▪ The costs of model complexity & backpropagation through calculus
  - o Why are deep learning models so useful?
    - ▪ Review of some theories
    - ▪ Leveraging Hierarchy
  - o Modern deep learning architectures & applications:
    - ▪ How can we ensure translational invariance? Convolutional NN
    - ▪ How can we encode temporal dependencies? Recurrent NN

▪ How can we create, rather than predict? Generative Adversarial Networks

Lecture #6 (2/26/20) - Reinforcement learning
• Lecture goal: An overview of the reinforcement learning problem and applications in engineering. This includes tie-ins with techniques from supervised learning, and recent successes with deep neural networks as environment models, value function approximators, and policy estimators.
• Lecture flow:
  o Brief intro to Markov decision processes (MDPs)
  o Definition of reward, state, actions, value, and policy
  o Modeling the environment
    ▪ Examples
  o Modeling the value function
    ▪ Deep Q learning successes (e.g. Atari games)
  o Policy gradient methods
    ▪ Deep learning policy gradient methods
    ▪ A3C algorithm and AlphaGo
  o Review some specific engineering applications
• (Possible HW):
  o Use Open AI Gym and ML library of choice to get a Q-Learning ML agent working on an Atari game
• Reference: Reinforcement Learning, An Introduction (Links to an external site.)

Lecture #7 (3/4/20) - Intersections of data science and software engineering
• Lecture Goal: provide a guide for successful collaboration between data scientists and software engineers.
• Required reading: selected overviews of different workflow and project management methodologies (e.g. waterfall vs agile vs purely exploratory vs ...) to highlight how there are multiple methods available for successfully planning and managing projects - and each has its own timelines, expectations, and paths to the end goal.
• Lecture Flow:
  o High level overview of what industry expects from "data scientists" vs "software engineers"
  o Examples of why it's important for data scientists and software engineers to work together and find a common language (e.g. some fun examples of where things went wrong and why)
  o Timeline expectations - examples of typical development cycles between the two competencies (specifically highlighting how expectation setting is important and describing why timeline expectations are different)
  o Natural divisions of labor and how to speak each other's language
  o Recipes for success - ensuring ML work can make it to a production application and 'play nice' in demanding environments (e.g. memory, processor, disk, network concerns)
  o Applied example of weekly cross-domain coordination on Pit Rho product, include here not only the roles of software developers and data scientists, but also analysts and domain experts

Lecture #8 (3/11/20) - From Research to Reality
Lecture Goal: To provide insight into the research world, start-up life, and industry, with regards to data science.

Lecture Flow: Case Studies in Academia, Start-Up, and Industry.

• Academia: A deep dive into an academic research problems and their solutions
• Start-Up: Understanding the start-up lifestyle and responsibilities
• Industry: The challenges of applying data science in industry

Lecture #9 (4/1/20) - Machine learning for chemistry and materials science 1: an overview
• Lecture goal: provide an overview of ML applications in materials and chemicals design and discovery, including discussion of successful and unsuccessful efforts
• Required reading:
  o *Materials Genome Initiative white paper* (https://www.mgi.gov/sites/default/files/documents/materials_genome_initi ative-final.pdf (Links to an external site.))
  o *Accelerating the discovery of materials for clean energy in the era of smart automation* (https://www.nature.com/articles/s41578-018-0005-z (Links to an external site.))
• Lecture flow:
  o Overview of computational materials science techniques and how they have evolved in the last few decades: going from solving the H atom to modern-day Kohn-Sham DFT
  o Frame the problem of materials/chemicals discovery: when intuition is poor,

humans result to guessing. When screening materials there is a speed vs accuracy trade-off - for certain problems you need speed and can sacrifice accuracy (especially when material space is large)
o Discuss ML approach and how this is different/similar from existing approaches
o Provide examples, discuss companies doing this
o Begin discussion of technical issues
• Homework (one assignment for both lectures): ~1000-word paper discussing how ML could apply to your individual engineering field of interest. Think beyond "how do we answer questions" and delve into "why do we want to answer this question"? This is the domain where ML shines. Highlight cases where the conventional wisdom/approaches have been unsuccessful and cite work when possible. This may help you see your field in a new light.

Lecture #10 (4/8/20) - Machine learning for materials science 2: deep dive in batteries
• Lecture goal: provide a real-life example of how ML can accelerate materials development by discussing Austin's work in batteries
• Required reading:
o *Holistic computational structure screening of more than 12,000 candidates for Li-ion conductor materials* (http://pubs.rsc.org/en/content/articlehtml/2017/ee/c6ee02697d (Links to an external site.))
o *Machine learning-assisted discovery of many new solid Li-ion conducting materials* (https://arxiv.org/abs/1808.02470 (Links to an external site.))
• Lecture flow:
o Continue discussion of technical issues around ML: this is small data and we have to be careful not to overfit at all costs
o Begin with a dive into battery science
o Discuss Austin's battery paper to highlight the technical issues around ML for materials
o End with class discussion of other directions in hard science where this approach may be valuable
• Homework: Continue writing assignment from previous week

Lecture #11 (4/15/20) - Transfer learning and AutoML
• Lecture goal: Provide an introduction to the importance of transfer learning in industry, science, and engineering, with the focus on the applications of image recognition, self-driving cars, and physics models.
• Lecture flow:
o Description of transfer learning, why it's useful, how it relates to human reasoning (reading (Links to an external site.))
▪ Successes in image recognition (reading (Links to an external site.))
▪ Example applications in self driving cars (segmentation), engineering problems with small datasets (car/airplane model prediction)
▪ Example applications in physics and materials science
o General description of AutoML (meta-learning)
▪ Why is it needed, what are recent developments
▪ The CNN/RNN loop
▪ Applications to hyperparameter tuning, data processing pipelines, state of the art results in a variety of applications (reading1 (Links to an external site.), 2 (Links to an external site.)

Lecture #12 (4/22/20) - Applied example, Pit Rho
• Lecture Goal: Review how data science and machine learning are used for in-race strategy, with an application to NASCAR.
• Required reading: introductory presentation
• Lecture Flow:
o High level overview of NASCAR and NASCAR strategy
o Overview of how technology drives decision-making in NASCAR
o The case for real-time strategy tool
o Key strategy considerations
o How it plays out in a race
o Lessons to be more broadly applied
• Homework: Continue the homework from week one.

Lecture #13 (4/29/20) - [topic TBD] -

MECE E6614: Introduction to Robotics

Meeting Time: Tuesday 4:10 pm - 6:40 pm, Venue: Fayewether 310

Instructor:	Sunil K. Agrawal, Ph.D. Professor of Mechanical Engg./Rehabilitation and Regenerative Medicine Office: 230 Mudd Hall Email: Sunil.Agrawal@Columbia.edu
Office Hrs:	Tuesday 2:00 – 3:00 pm, 230 Mudd Hall
TA:	Haohan Zhang: hz2347@columbia.edu Antonio Prado: jap2254@columbia.edu
Textbook:	Robot Dynamics & Control, M. W. Spong and M. Vidyasagar, Wiley 1989
Prerequisites:	All students must have taken introductory classes in Dynamics/Control

Schedule:

9/6	Introduction to Robotics: Chapter 1
9/13	Rigid Motions and Homogeneous Transformations: Chapter 2
9/20	* Work in Groups: Project 1
9/27	Angular Velocity and Linear Velocity: Chapter 2 Contd.
10/4	Forward Kinematics: Chapter 3
10/11	Inverse Kinematics: Chapter 4
10/18	Velocity Kinematics – Jacobians: Chapter 5
10/25	Dynamics: Chapter 6
11/1	* **Mid-Term Exam**
11/8	**University Holiday- Election Day**
11/15	Dynamics: Chapter 6 Contd. Independent Joint Control: Chapter 7
11/22	Independent Joint Control: Chapter 7 Contd.
11/29	* Work in Groups: Final Project
12/6	**Final Project Presentation**

Grading:

Homework:	20%
Project 1	10%
Mid-Term Exam:	30%
Final Project	40% (Includes presentation/Technical report)

Other Course Details:

(i) **Homework** will be assigned after the completion of a topic. These will be due in a week after the assigned date.

(ii) **Project 1**: These will be performed in assigned groups of 4. You choose a paper from ICRA 2015 or 2016 Proceedings on a topic of interest to you and obtain permission from Instructor/TA to work on it. You may be able to pick papers based on sub-disciplines of robotics or application areas. Prepare 6 PowerPoint slides that include the following: Problem statement, Prior research, Solution approach, Results, Conclusions and Future Extensions.

(iii) **Mid-Term Exam**: This exam will be based on material of Chapters 1-6

(v) **Final Project**: The students will work in self-selected groups of 4. Define a problem that involves novel design, analysis, simulation, etc. using the principles that you have studied in this course. The problem should have a good motivation and should be approved by the Instructor/TA.

Presentation - Prepare 6 PowerPoint slides that include the following: Problem statement, Your solution approach, Results, Conclusions and Future Extensions. *Technical Paper* - Write a 4-page technical report in word (2 column 10 point) using the typical format of ICRA paper.

(v) **Course Ethics**: Discussion of the lecture material among students is encouraged.
However, home-works must be performed individually.

MECE-E4603 Applied Robotics: Algorithms and Software

Course Designator: MECE
Course Prefix: E
Course Number: 4603
Course Semester: x
Title: Applied Robotics: Algorithms and Software
Lecture Hours: standard (13/14 lectures)
Lab Hours: 0 **Points:** 3
Instructor: Matei Ciocarlie
Prerequisites: Fundamental programming skills (e.g. COMS W1002 or COMS W1004 or COMS W1005 or ENGI E1006 or equivalent).

Corequisites: none

Program Restrictions: none

Textbook: none

Evaluation: Applied projects (70%), quizzes (30%)

Bulletin Description: The science and systems aspects of Robotics taught from an applied perspective, focusing on algorithms and software tools. Spatial reasoning; tools for manipulating and visualizing spatial relationships. Analysis of robotic manipulators; numerical methods for kinematic analysis. Motion planning, search-based and stochastic approaches. Applications for force and impedance control. Grading based on a combination of exams and projects implemented using the Robot Operating System (ROS) software framework and executed on real and simulated robotic manipulators.

Notes: This course can be taken individually or simultaneously with MECE E4602 (Introduction to Robotics). This course can also be used to satisfy the requirements of the Robotics and Control concentration of the Mechanical Engineering Master of Science program.

Rationale: The Robotics industry is booming, with new application domains ranging from logistics and e-commerce to the hospitality industry and even the home, and unprecedented investment from both start-ups and major technology companies such as Amazon or Google. This course teaches the combined science and systems aspects needed for a roboticist to hit the ground running in this new ecosystem. It presents the core aspects of mobility and manipulation using modern tools such in both software (the Robot Operating System) and hardware (the Baxter robotic manipulator). While theoretical concepts are presented as needed, the focus is on learning the practical application of these concepts in assignments executed on real robots.

Syllabus:

9/5	Introduction
9/7	Introduction to ROS
	Assignment 0 (ungraded) released: basics of ROS
9/1 2	Transforms I
9/1 4	Transforms II
	Assignment 1: Transform Manipulation and Visualization in ROS
9/1 9	Kinematic Chains / Forward Kinematics
9/2 1	Analytic Inverse Kinematics
	Assignment 2: FK and Robot Visualization
9/2 6	Differential Kinematics
9/2 8	Linear Algebra Refresher I (matrices and vector spaces, linear systems)
10/ 3	Linear Algebra Refresher II (Singular Value Decomposition)
	Redundant Robots
10/ 5	Cartesian Control I
10/ 10	Cartesian Control II
	Numerical Inverse Kinematics
10/ 12	Assignment 3: Cartesian Control and Numerical IK

	Midterm review
10/ 17	Midterm quiz
10/ 19	CTV Robotics Symposium
10/ 24	Motion Planning I
10/ 26	Motion Planning II
10/ 31	Motion Planning III
11/ 2	Trajectory Execution
	Force Generation on Robot Arms
11/ 9	Assignment 4: Motion Planning
11/ 14	Mobile Robot Kinematics
	State Estimation I
11/ 16	State Estimation II, Probabilistic Reasoning
11/ 21	State Estimation III, the Kalman Filter
11/ 28	State Estimation IV, Extended Kalman Filter, Particle Filters
11/ 30	Final review
	Assignment 5: State Estimation
12/ 5	Final quiz
12/ 7	Recap and Conclusions

MECE E4604 Product Design for Manufacturing

Fall 2020

Times: Two and one half hour lectures every week
Location: TBD
Instructor: Prof. Graham Walker
Email: graham.walker@manhattan.edu (gw2156@columbia.edu)
Office: Mudd ME Adjunct Office, 248b
Tel: (718) 862-7405
Office Hours: 6:30 pm to 7:00 pm on Tuesdays

Textbook: Boothroyd, G., Dewhurst, P. and Knight, W.A. (2011), *Product Design for Manufacturing and Assembly*, CRC Press. (Suggested0
Poli, C. (2001), *Design for Manufacturing: A structured Approach*, Butterworth-Heinemann. (Suggested0
http://www.sciencedirect.com/science/book/9780750673419

Topics:
Introduction and Design Process
Material Properties and Manufacturing
Material Selection
Manufacturing Processes and Design
Non-Dimensional Groups, Scaling, and Standard Sizes
Group Technology
Design for Manufacture
Basic Probability and Statistics
Tolerance Stacking, and Process Capability
Robust Design
Design for Assembly/Automation, and Poka-Yoke

Grading:
Homework 25%
Midterm 30%
Final 40%
Project 5%

Assignments: Homework and projects are due on the date specified and are submitted online. There are no extensions; however, partial credit will be considered for all incomplete work. Assignments cannot be accepted after answers have been made available. Solutions will either be available online. If you disagree with a grade, submit your grievance in writing (e.g., an email) to the instructor, documenting the merits of your case.

Timetable

Week	Topic
1 (09/02)	Introduction, and the Design Process
2 (09/09)	Material Properties and Manufacturing
3 (09/16)	Material Selection (Ashby)
4 (09/23)	Manufacturing Processes and Design
5 (09/30)	Non-Dimensional Groups, Scaling, and Standard Sizes
	Homework 1 due on Sep 30, 2020
6 (10/07)	Group Technology
	Homework 2 due on Oct 07, 2020
7 (10/14)	Design for Manufacture (Poli)
	Homework 3 due on Oct 14, 2020
8 (10/21)	**Mid Term Exam (October 25)**
9 (10/28)	Design for Manufacture (Boothroyde)
10 (11/04)	Basic Probability and Statistics
	Project due Nov 04, 2020

11(11/11)	Tolerance Stacking, and Process Capability
12(11/18)	Robust Design (Taguchi)
	Homework 4 due on Nov 18, 2020
13(11/25)	*Thanksgiving Break*
14(12/02)	Boothroyd Video, and Design for Assembly and Poka-Yoke
	Homework 5 due on Dec 02, 2020
15(12/09)	***Reading Days***
16(12/16)	**Final Exam**

MECE 4606 – Digital Manufacturing

1. **Credits:** 3
2. **Contact Hours:** 2.5 hours/week
3. **Instructor's name:** Hod Lipson
4. **Textbook Information:** N/A
   a. **Other Supplemental Materials:** Lecture slides

5. **Specific Course Information**
   a. **Course Description:** Covers a variety of digitally controlled manufacturing processes that convert computer models directly into physical objects. Topics include: Additive manufacturing processes, CNC, Sheet cutting processes, Numerical control, Generative and algorithmic design. Topology Optimization, Broader social, economic, legal and business implications will also be reviewed. Course involves both theoretical exercises and a hands-on project
   b. **Prerequisites:** Programming Experience
   c. **Co-requisites:** N/A d. **Course Required or Elective:** Elective

6. **Specific Goals for the Course**
   - **Specific Outcomes of Instruction:** The student will be able to understand and apply digital manufacturing approaches to engineering design.
   - **Student Outcomes Addressed by Course:** a, b, c, e, k, m

7. **Brief list of topics to be covered**
   1. Overview of digital manufacturing processes
      a. What makes a manufacturing process "digital"
      b. The 10 disruptive principles of digital manufacturing processes

   2. Additive Manufacturing processes – Engineering polymers, metals, ceramics
      a. Stereolithography
      b. Selective Laser Sintering
      c. Fused Deposition Modeling
      d. Polyjet e. LENS
      f. Layered object manufacturing

   3. Additive Manufacturing processes – Advanced materials a. Electronic Materials b. Bioprinting c. Food Printing

   4. Material properties
      a. Mechanical properties of printed materials
      b. Post processing
      c. Empirical and data-driven models

   5. CNC
      a. Mill
      b. Lathe

   6. 2D Cutting
      a. Laser Cutting
      b. Plasma Cutting
      c. Waterjet

   7. Programmable Assembly
      a. Digital Assembly
      b. Digital Bending

   8. Fundamentals of geometric representations for digital manufacturing
      a. Solid representations
      b. Boundary representations
      c. Function representations
      d. Voxel representations

   9. Algorithmic design for digital manufacturing
      a. Parametric Models

b. Vibrational Geometry
c. Generative models
d. Topology optimization

10. Machine Control
    a. Gantry positioning approaches
    b. STL/AMF Slicing

11. Broader impacts
    a. Safety, Liability and intellectual property
    b. Environmental impact
    c. On-demand fabrication models and mass customization

MECE E4609 Computer Aided Manufacturing

Spring 2021

Times: Wednesdays, 7:00 to 9:30pm
Location: TBD
Instructor: Prof. Graham Walker
Email: graham.walker@manhattan.edu or gw2156@columbia.edu
Office: Mudd 248b
Tel: (718) 862-7405
Office Hours: Wednesday, 6:30 – 7:00 pm

Textbook: Groover, M.P. (2008), *Automation, Production Systems, and Computer-Integrated Manufacturing*, 3rd Ed., Prentice Hall (this is only suggested)

Software: ProModel Student Package (CD Only)
https://www.promodel.com/store/shopdisplayproducts.asp?id=13&cat=ProModel+Academic+Packages

Topics:
Introduction (2 hr)
CAM Software (1 hr)
Manufacturing Processes (6 hr)
Fundamentals of Numerical Control (2 hr)
NC Programming (2 hr)
Robots (6 hr)
Vision Systems (3 hr)
Instrumentation (3 hr)
Programmable Logical Controllers (3 hr)
SQC (6 hr)
Process Planning (3 hr)
Rapid Prototyping (1 hr)

Grading:

Homework	25%
Midterm	30%
Final	40%
Projects	5%

Policy: Homework and projects are due in class on the date specified. Homework and projects may be submitted as a hard copy, as specified in class. There are no extensions; however, partial credit will be considered for all incomplete work. Assignments cannot be accepted after answers have been made available. Solutions will either be distributed in class or made available online. If you disagree with a grade, submit your grievance in writing (e.g., an email) to the instructor, documenting the merits of your case.

Computers: Computer use is expected but MATLAB and SPSS will be the only on-campus programs that will be required.

Timetable

Week	**Topic**
1 (01/20)	Introduction
2 (01/27)	Manufacturing Processes
3 (02/03)	Manufacturing Processes
4 (02/10)	CNC Control and Programming (Homework 1 Due)
5 (02/17)	Basic Robotics and Robot Kinematics
6 (02/24)	Robot Kinetics (Homework 2 Due)

7 (03/03)	Vision Systems
8 (03/10)	Pattern Recognition in Manufacturing (Homework 3 Due)
9 (03/17)	***Spring Break***
10(03/24)	**Mid Term Exam**
11(03/31)	Instruments and Sensors
12(04/07)	Programmable Logic Controllers (Projects Due)
13(04/14)	Measurement and Statistics
14(04/21)	Quality Control (Homework 4 Due)
15(04/28)	System Control and Fuzzy Logic
16(05/05)	***Reading Days*** (Homework 5 Due)
17(05/12)	**Final Exam**

ME E4610 Advanced Manufacturing Processes

Instructor: Professor Y. Lawrence Yao
Office: 242 Mudd
Office hours: Thursdays, 1:00-2:30 pm
Office phone: (212) 854-2887
Email address: ylyl@columbia.edu

Day and Time: Tuesdays, 4:10 – 6:40 pm, Room 524 Mudd

Reference books: H. Hocheng, and H.-Y. Tsai, Advanced Analysis of Nontraditional Machining, Springer, 2013 (electronically available at Columbia Library CLIO)

E. Kannatey-Asibu, Jr., Principles of Laser Materials Processing, Wiley, 2009 (electronically available at Columbia Library CLIO)

W. Steen and J. Mazumder, Laser material processing, 4th ed., Springer, 2010 (electronically available at Columbia Library CLIO)

Topic areas from: Introduction
Electrochemical machining Principles of industrial lasers Beam characterization, shaping, and delivery Types of industrial lasers Heat and fluid flow Laser materials processing Laser machining, welding, and surface modification

Grading: Homework (the lowest one will be dropped) 15%
Midterm exam 35%
Final exam 50%

Homework submission: Electronic submissions via Coursework only. The site stops accepting submissions by midnight of the due date. No late submissions will be accepted. Note: the lowest scored homework set will not be counted as seen above.

Dates: Wednesday, October 31, Midterm Exam
Wednesday, December 19, Final Exam

Tentative Schedule

Session	Date	Homework	Note
Introduction, ECM	Wed, 9/5	HW1 assigned	
ECM	Wed, 9/12		
Laser Basics	Wed, 9/19	HW1 due	
Laser Basics (cont.) Practical Lasers	Wed, 9/26	HW2 assigned	
Practical Lasers (cont.)	Wed, 10/3		Laser demo
Laser Properties	Wed, 10/10	HW2 due HW3 Assigned	
Laser Properties (cont.)	Wed, 10/17		
Laser Mfg	Wed, 10/24	HW3 due	
Midterm	Wed, 10/31		
No Class (Election Day)	Wed, 11/7		
Laser Mfg (cont.)	Wed, 11/14	HW4	
Laser Mfg (cont.)	Wed, 11/21		Process demo
Laser Mfg (cont.)	Wed, 11/28		
Laser Mfg (cont.)	Wed, 12/5	HW4 due HW5 assigned	
	Wed, 12/12	HW5 due	
Final exam	**Wed, 12/19**		

MECE E4611 Robotics Studio

Mondays 10:10-11:25am Location 415 Schapiro

This is a studio course that will expose you to the entire robot design process from A to Z, including kinematics, industrial design, manufacturing, electronics, and programming. Project can be done individually or in pairs, for three credits.

Your goal is to design and construct an organic-looking legged robot. This semester we will be building 12-motor robots similar to Boston Dynamics' *Spot* and ETH's *ANYmal*

The robot will use serial bus revolute servomotors with a 240-degree range, a rechargeable battery, and Raspberry Pi controller. It may also incorporate a touchscreen display, a camera, and an accelerometer. Your goal is to make a robot that simply moves. You can optionally make the robot do something more interesting, such as recognize objects or learn to walk. You can even use a 3D printer to make interesting textures, such as lattices, scales, fur, and any kind of alien skin.

Course staffing

- Lecturer: Prof Hod Lipson, hod.lipson@columbia.edu
- Course Assistant: TBD
- Grader: TBD

Milestones

1. Week 1: Understand the basic components (see next page) and specifications. Sketch out a few potential designs in pencil and paper. Propose at least four different designs. Calculate weight and make sure motors and structure can handle the loads. For an organic look, minimize the use of straight edges, orthogonal corners, and flat surfaces. Iterate.
2. Week 2: Create a rough CAD model of a selected design. Download CAD models of components (Raspberry Pi, Motors, Controller board, etc). Revise concepts if necessary.
3. Week 3-4: Refine your CAD model. Include motor and PCB mounts, holes for thermoplastic screw inserts, cables and cable harnesses, covers and fairings. Revise concept if necessary.
4. Week 5-6. Print portions of your robot (e.g. joints and mounts) to test form and fit, and test basic code functionality and electronic wiring.
5. Week 7-8. Print and assemble your entire robot. Test motor connectivity.
6. Week 9-10: Program your robot to move in a simple gait
7. Week 11-12 Simulate your robot and optimize the gait.
8. Week 13-14 improve, revise and adjust.

grading

Grading of the project is based on process and accomplishments.

- 50% Bi-weekly assignments
- 50% Final untethered walking robot performance

Academic Integrity

You are not allowed to copy code, CAD files, or design concepts from other sources. Everything you generate must be your own. However, you are allowed to reuse CAD models of subcomponents, and you may be inspired by other designs, but cite your sources.

Late Submissions

You are provided 96 grace hours for late submission which you can use for any reason you like. You can earn more hours by submitting early or use up hours by submitting late.

If you have used up all your hours, there is a late penalty of 5 percent per day. Once you reach 10 days late, the penalty will remain at 50% until you submit.

Last submission accepted is May 11.

MECE E4811 Aerospace Human Factors Engineering

Course Designator: MECE
Course Prefix: E
Course Number: 4811
Course Semester: Fall
Title: Aerospace Human Factors Engineering
Lecture Hours: standard (13/14 lectures)
Lab Hours:0 **Points**: 3 **Instructor**: Mike Massimino
Prerequisites: junior standing
Corequisites: none
Program Restrictions: none

Bulletin Description:

Engineering fundamentals and experimental methods of human factors design and evaluation for spacecraft which incorporate human-in-the-loop control. This course will provide a fundamental understanding of the human factors specific to space flight that must be taken into consideration in the design of spacecraft which incorporate human-in-the-loop control. Students will be taught how to design human factors experiments utilizing task analysis and user testing with quantitative evaluation metrics to develop a safe and high-performing operational space system. Topics include human-centered design, functional allocation and automation, human sensory performance in the space environment, task analysis, human factors experimental methods and statistics, space vehicle displays and controls, situation awareness, workload, usability, manual piloting and handling qualities, human error analysis and prevention, and anthropometrics.

Rationale:

As spacecraft, aircraft, and robotics become more complex, they also add complexity to the tasks of human who control and operated them. Upon completion of this course, students should be able to:

- o Understand human sensory capabilities and limitations in the space environment.
- o Properly design human factors experiments and perform related statistical analyses.
- o Perform a task analysis to derive a set of requirements for a human spacecraft interface.
- o Perform a functional analysis to properly utilize the strengths of both the astronaut and automation.
- o Design static prototypes of spacecraft displays and controls using a set of human factors heuristics.
- o Identify sources and types of human error and design controls to prevent human error in space systems operation.
- o Accommodate the full range of human anthropometrics for crew interface designs.
- o Evaluate usability, workload, and handling qualities using industry-standard quantitative metrics.
- o Combine all of these objectives in a well-written human factors test report.

Syllabus:

Part 1: Role of the Crew in Spacecraft Operation

- Functional Allocation and Group Project Outline
- Human Sensory Performance
- Task Analysis and Human Physiological Effects of Spaceflight

Part 2: Design of Displays for Spacecraft Operation

- Design of Controls for Spacecraft Operation and Human Factors Experimental Methods
- Statistics

Part 3: Workload and Related Testing Methods

- Usability and Manual Piloting
- Handling Qualities, Situation Awareness, Human Error Analysis and Prevention

Part 4: Automation and Human/Machine Collaborative Control

- Anthropometrics: Basics
- Anthropometrics: Applications

Goal
The goal of this course is to allow students to expand their professional experience by participating in an internship at an industrial or research institution outside the university.

Requirement
Students registered in this class must enroll and participate in a technical role at an external entity.

Grading
Students must submit a written report, elaborating on the internship experience, projects, and their relevance to their degree program.
The final report must be accompanied by an assessment letter written by the student's direct supervisor. The letter should be submitted directly to Melbourne Francis at mef2@columbia.edu.

Report guidelines
Your grade for MECE E4999 Fieldwork depends on the quality of the report. Hence, it is important that you describe your internship experience clearly and purposefully. Your report should contain approximately **2500 words**, plus figures, diagrams and references. Your report should contain only non-confidential information.

1. **Cover page** with the following information (only): MECE E4999 – Fieldwork, Semester, Instructor: Prof. Hod Lipson, Company/location of internship, Internship start/end date, your job title or focus area, your name, UNI, date submitted,
2. **Executive summary** (<250 words) summarizing each section below in one or two sentences.
3. **Responsibilities.** Your internship goals and responsibilities. If your internship was quantitative, please explain the concepts and clarify using equations, technical information, diagrams and photos. Clearly explain concepts, equations, symbols, abbreviations. Pretend that the audience reading your report has no knowledge of your work.
4. **Typical day:** Describe a day of this internship. Did you have routines, meetings, reports, presentations?
5. **Organization.** Explain how your work fits within the organization. How did your work contribute to the business of the organization? Who did you work with?
6. **Career contributions.** Discuss how this internship contributes to your career goals and coursework at Columbia. Include your accomplishments.

General instructions: Include page numbers. Single spacing 12pt font. Use only your own words. Do not copy content from the company website or the Internet. Proofread before submitting. Ensure supervisor is aware that they need to submit a final assessment directly to Mel in order for you to receive a grade.

Good luck!
Hod Lipson

MECE E6100 ADVANCED MECHANICS OF FLUIDS

Notice

Academic Integrity

The follow constitutes cheating:

Copying assignments from others. Consulting solutions sets and laboratory reports from previous years. Consulting exams from previous years that were not made available by instructor. Completing individual assignments in a group, when permission not explicitly granted by instructor. Plagiarizing the work of others.

Cheating may lead to the following consequences:

Student receives a failing grade for a specific assignment. Student receives a failing grade for an entire course. Student may be expelled from the university. The Department of Mechanical Engineering adheres to Columbia's policies on academic integrity, see http://www.college.columbia.edu/academics/integrity.

Student Bill of Rights

- Academic integrity policies clearly explained at start of semester
- Course requirements/grading policies/etc. must be clearly stated at start of semester.
- Textbook/reference book usage must be clarified at start of semester.
- Homework assignments will be graded on a weekly basis (unless valid explanation provided).
- Midterm exams will be graded within two weeks of test (unless valid explanation provided).
- Final exams will be graded within the deadlines set by the university.
- Instructor and teaching assistants must provide office hours or otherwise explain procedure for meeting with students.
- Instructors will provide pertinent information on assignments and lab reports in a timely manner.

Honor Code

- Honor code: **https://www.cc-seas.columbia.edu/integrity (https://www.cc-seas.columbia.edu/integrity)**
- Also review the guidelines posted here: **http://www.columbia.edu/cu/studentconduct/documents/StandardsandDiscipline.pdf (http://www.columbia.edu/cu/studentconduct/documents/StandardsandDiscipline.pdf)**
- All coursework is to be done by the student working alone. For homework assignments, you may consult other students for general guidelines or to review and discuss material covered in class, but homework assignments must be completed individually.
- No external aids or electronic devices are allowed in exams.
- Do not look up homework solution sets posted from previous years or posted elsewhere.
- Consult the instructor if you require clarifications regarding the honor code.
-

Course Grading

- Homework 30%
- Midterm Exam 30%
- Final Exam 40%

Chapter 1: Tensors

- Indicial Notation
- Tensors

Chapter 2: Stress

- Forces and Traction
- Cauchy Stress Tensor
- Principal Stresses

Chapter 3: Balance Laws for a Continuum

- Differential Operators of Scalar, Vector and Tensor Functions

- Balance of Mass
- Balance of Linear Momentum
- Balance of Angular Momentum
- Balance of Energy
- Entropy Inequality

Chapter 4: Kinematics of the Continuum
- Motion and Path Lines
- Deformation Gradient
- Rate of Deformation
- Volume Deformation
- Velocity Gradient
- Vorticity

Chapter 5: The Viscous Fluid
- Constitutive Restrictions
- Incompressible Fluid
- Isotropic Materials
- Inviscid Fluids
- Newtonian Fluids
- Non-Newtonian Viscous Fluids

Chapter 6: Solution of Problems in Incompressible Newtonian Fluid Mechanics
- Navier-Stokes Equations
- Boundary Conditions
- Problems in Cartesian Coordinates
    - Plane Couette Flow
    - Plane Poiseuille Flow
    - Flow Near an Oscillating plate
- Problems in Cylindrical Coordinates
    - Circular Poiseuille Flow
    - Circular Couette Flow

Chapter 7: Inviscid Incompressible Flows
- Vorticity and Circulation
- Bernoulli's Equation
- Kelvin's Circulation Theorem
- Vorticity Equation

Chapter 8: Inviscid Compressible Flows
- Speed of sound in ideal gas
- Steady isentropic nozzle flow

Course Summary:
Date Details
Wed Sep 11, 2019 **Homework 1**
https://courseworks2.columbia.edu/courses/85350/assignments/301463 due by 1:10pm

Wed Sep 18, 2019 **Homework 2**
https://courseworks2.columbia.edu/courses/85350/assignments/301464 due by 1:10pm

Wed Sep 25, 2019 **Homework 3**
(https://courseworks2.columbia.edu/courses/85350/assignments/301465 due by 1:10pm

Wed Oct 2, 2019 **Homework 4**
https://courseworks2.columbia.edu/courses/85350/assignments/301466 due by 1:10pm

Wed Oct 9, 2019 **Homework 5**

https://courseworks2.columbia.edu/courses/85350/assignments/301467 due by 1:10pm

Wed Oct 16, 2019 **Midterm Examination**
https://courseworks2.columbia.edu/courses/85350/assignments/301473 due by 3:40pm

Wed Oct 30, 2019 **Homework 6**
https://courseworks2.columbia.edu/courses/85350/assignments/30146 due by 1:10pm

Wed Nov 6, 2019 **Homework 7**
https://courseworks2.columbia.edu/courses/85350/assignments/301469 due by 1:10pm

Wed Nov 13, 2019 **Homework 8**
https://courseworks2.columbia.edu/courses/85350/assignments/301470 due by 1:10pm

Wed Nov 20, 2019 **Homework 9**
https://courseworks2.columbia.edu/courses/85350/assignments/301471 due by 1:10pm

Wed Dec 4, 2019 **Homework 10**
https://courseworks2.columbia.edu/courses/85350/assignments/301472 due by 1:10pm

Wed Dec 18, 2019 **Final Examination**
https://courseworks2.columbia.edu/courses/85350/assignments/301462 due by 4pm

MECE E6102 Computational Heat Transfer and Fluid Flow

Spring 2020
Tuesday 4:10 PM – 6:40 PM (Engineering Terrace 252)
Instructor Dr. Dustin W. Demetriou
Office Hours: Tuesday 3:30 PM – 4:00 PM (Mudd 248b) or by Appointment dd2980@columbia.edu

Course Description

Mathematical description of pertinent physical phenomena. Basics of finite- difference methods of discretization, explicit and implicit schemes, grid sizes, stability, and convergence. Solution of algebraic equations, relaxation. Heat conduction. Incompressible fluid flow, stream function- vorticity formulation. Forced and natural convection. Use of primitive variables, turbulence modeling, and coordinate transformations.

Course Objectives

1. Learn the basic concepts of numerical analysis for the solutions of problems in heat transfer and fluid flow. Write computer code to solve relevant physical equations in heat transfer and fluid flow.
2. Learn how to properly set up and solve problems relevant to industry applications in heat transfer and fluid flow using commercial computational fluid dynamics software.
3. Understand how commercial software implements numerical algorithms and what an engineer needs to know to properly use these tools.

Prerequisites	MECE E3100, MECE E3311 and COMS W1005
Textbook (Not Required)	D. Anderson, J. Tannehill, R. Pletcher. Computational Fluid Mechanics and Heat Transfer, Third Edition. CRC Press.
Course Website	All course material will be available on CourseWorks
Software	ANSYS Fluent, ANSYS Meshing (Required) SpaceClaim (Suggested) or equivalent (such as Pro-E) Python3 and Jupyter Notebooks (Suggested) or equivalent programming language (Matlab, Java)
Grading Policy	Homework (50%) One Exam (20%), closed book, in-class Final Project (30%)

Attendance policy

Students are required to show up on time and prepared for all classes. This course will utilize scheduled time in the computer lab. A student who is absent from class cannot necessarily expect the course instructor to provide notes or make available additional scheduled time for completing computer assignments.

Academic integrity

Integrity and ethical behavior are particularly important in engineering; and, as such, any form of cheating, plagiarism, fabrication, or academic misconduct will not be tolerated.

Other references

Tu, Yeoh, and Liu. Computational Fluid Dynamics: A Practical Approach, 2nd Edition. Elsevier, 2013.
Verrsteeg and Malalasekera. An Introduction to Computational Fluid Dynamics: The Finite Volume Method. Prentice Hall, 1995.

Topic **Week**	
1	Introduction to CFD and its applications Review of heat transfer, fluid flow, and governing equations Introduction to ANSYS Workbench
2	Classification of PDEs (elliptic, hyperbolic, parabolic) Discretization methods (finite difference vs. finite volume)
3	Solution of 1D steady state diffusion equation (Central differencing) Thomas algorithm for tri-diagonal matrix solutions
4	Steady 1D convection-diffusion equation (Central differencing) Consequences of discretization

	Steps for solving problems using CFD (pre-processing, solution, post-processing)
5	Steady 1D convection-diffusion equation
	Upwind schemes and higher order schemes (QUICK scheme)
	Iteration techniques (Jacobi Method)
6	Introduction to multi-dimensional problems
	Finite volume discretization of 2-D unsteady heat diffusion problem
	Solution of 2-D problems in Fluent
7	1-D unsteady convection problems
	2nd-order Crank-Nicholson implicit scheme, Lax-Wendroff explicit scheme
8	**Mid-term exams**
	Fluent Example: Flow over a heating coil
9	Introduction to grid generation software
	ANSYS Meshing Example(s): Inflation and sizing options
10	Conduction heat transfer modeling in Fluent
	Applications of CFD in electronics cooling
	Fluent Example: Conduction in a heat sink
	Final project overview
11	Incompressible Navier-Stokes equations and SIMPLE algorithm
	Convection heat transfer modeling in Fluent
	Fluent Example: Flow through a heat exchanger
12	Overview of natural convection modeling in Fluent
	Application of modeling air flow in the indoor environment
13	Overview of radiation modeling in Fluent
14	Introduction to turbulence modeling (focus on k-e implementation in Fluent)

Course Assignments

Week Assigned / Week Due	Assignment
1 / 3	CFD and Meshing Tutorial (ANSYS Fluent and Mesher)
3 / 5	Numerical solution of steady 1D diffusion equation with source
5 / 7	Numerical solution of steady 1D convection / diffusion equation
7 / 9	Numerical solution of steady 2D conduction equation
9 / 11	Grid independence study (ANSYS Mesher and Fluent)
12 / 14	Evaluation of indoor air flows (ANSYS Mesher and Fluent)

Final Project

The final project will address a thermal/fluids problem of industry significance. Students will utilize the commercial CFD software ANSYS Fluent to study the problem numerically. The problem will be sufficiently complex and challenging with no analytical solution; therefore, requiring students to justify the answer to the problem obtained using the CFD software via methods such as, but not limited to, first principles, dimensional analysis, and grid independence studies. Students are expected to complete the entire workflow including geometry creation, grid generation, solution, and post processing. A written report is required detailing the problem, solution procedure, and a discussion of the results.

MECE E6104 CASE STUDIES IN COMPUTATIONAL FLUID DYNAMICS

FALL 2020

Objective: Preparation for application of computational fluid dynamics to real world problems, to provide students with the skills necessary to conduct a CFD analysis in an industrial (real world) situation.

Approach: Series of lectures covering techniques coupled with tutorials and case studies to demonstrate the application. Lectures of approximately one to two hours each (Computer Lab Room 252 Engineering Terrace), followed by tutorial sessions where applications will be demonstrated through instructor-led sessions and student participation. Tutorials will also afford the opportunity for students to work on their assignments and ask questions.

Assessment: Assignment and participation based throughout the semester and then a major project at the conclusion.

Assignment 1	= 15% of grade
Assignment 2	= 10% of grade
Assignment 3	= 15% of grade
Assignment 4	= 10% of grade
Quiz	= 10% of grade (take home quiz covering materials presented in class)
Major project	= 40% of grade

Software: There is no mandatory software package. Students are encouraged to try different packages to increase exposure and capability. The course will mostly use ANSYS Fluent and NIST Fire Dynamics Simulator. Both packages are commonly used in industry.

Textbook: Slides and handouts will contain essential material with sources referenced. Textbooks from fluid mechanics and heat transfer classes will be particularly helpful. Suggested reading will include sections from the book: Computational Fluid Dynamics: A Practical Approach, 3rd Edition, Tu, Yeoh, Liu (available via the library online collection). Some other useful references useful for this course include:

- Computational Methods for Fluid Dynamics, Ferziger and Peric, 2001
- Computational Fluid Dynamics in Building Design, Chitty, 2014

CASE STUDIES IN COMPUTATIONAL FLUID DYNAMICS MECE E6104 FALL 2020

Lecture / Tutorial Outline

In each lecture one or more of the following subject categories will be covered:

1. Theory (as needed to support case studies, cover relevant CFD fundamentals)
2. Practices (such as Perl, Python, DOS, software know-how)
3. Cases (the case studies and tutorials)
4. Delivery (topics relevant to project delivery such as QA/QC, version control)
5. Of interest (CFD and general topics of interest such as the top 500 computers, FYFD)

Tutorials

Hands-on working sessions to demonstrate application of CFD software to case studies – the syllabus shows the outline, but specific topics will be tailored based on needs identified throughout the semester with respect to assignments and items of interest which arise.

CASE STUDIES IN COMPUTATIONAL FLUID DYNAMICS MECE E6104 FALL 2020

Course Outline

Preliminary – note that the schedule of topics for each lecture / tutorial / assignment may change depending on progress throughout the semester – items in red are under revision

Lecture / tutorial	Theory	Practice	Cases	Delivery	Of interest
1 Introduction 9/7	Methods of prediction 1D heat transfer Numerical methods – heat transfer example Boundary conditions	CFD software roadmap and overview of packages used	1: 1D heat transfer 2: 2D heat transfer into a concrete structure – intro to ANSYS	Verification and validation	Wind tunnel phone app
Assignment 1 (issued): 1D heat transfer equation					

Suggested reading: Computational Fluid Dynamics: A Practical Approach, Chapter 1, Chapter 2 – Section 2.1 ANSYS Fluent User Guide, Chapter 1, Chapter 2 ANSYS Fluent Theory Guide, Chapter 1					
2 CFD fundamentals and intro to ANSYS Fluent 9/14	Pressure loss in pipe / tunnel flow situations	Grid concepts	3: Pressure loss through a fitting (ANSYS Fluent)	Naming and version control Documentation and reporting	FYFD
Suggested reading: ANSYS Fluent User Guide Chapter 3, Chapter 4, Chapter 5 Computational Fluid Dynamics: A Practical Approach, Chapter 2 – Section 2.2, Section 2.3, Section 2.4 Computational Fluid Dynamics: A Practical Approach, Chapter 3 – Section 3.1, Section 3.2, Section 3.3					
3 CFD fundamentals and intro to Fire Dynamics Simulator 9/21	Naiver-Stokes equations and numerical methods Boundary conditions Convergence	Parallel computing Fire Dynamics Simulator – getting started DOS / Unix	4: Pressure loss through a bend (Fire Dynamics Simulator)	Quality control Design impacts	Top 500 computers

CASE STUDIES IN COMPUTATIONAL FLUID DYNAMICS MECE E6104 FALL 2020

Lecture / tutorial	**Theory**	**Practice**	**Cases**	**Delivery**	**Of interest**
Assignment 2 (issued): Pressure change through a fitting – ANSYS Fluent and Fire Dynamics Simulator Suggested reading: ANSYS Fluent User Guide – Chapter 7.3 Fire Dynamics Simulator, Version 6, User's Guide, Chapter 1 through 7					
4 Intermediate physics 9/28	Turbulence introduction	Fire Dynamics Simulator – basics (continued)	4: Pressure loss through a bend (Fire Dynamics Simulator) 5: Flow over an inclined facing step – introduction	Budget for a project Tracking progress	Stanford CTR Gallery of fluid motion
Suggested reading: Fire Dynamics Simulator, Version 6, User's Guide, Chapter 8, Chapter 9, Chapter 17					
5 Intermediate physics 10/5	Turbulence modeling Near-wall turbulence	Sensitivity analysis 6: ANSYS Fluent	6: ANSYS Fluent simulations of channel flow and inclined facing step / turbulence models and numerical methods	Marketing and conferences	Engineering disasters
Assignment 3 (issued): TBA Suggested reading: Computational Fluid Dynamics: A Practical Approach, Chapter 3 – Section 3.5 ANSYS Fluent User Guide – Chapter 8, Chapter 28, Chapter 30 through 32					

CASE STUDIES IN COMPUTATIONAL FLUID DYNAMICS MECE E6104 FALL 2020

Lecture / tutorial	**Theory**	**Practice**	**Cases**	**Delivery**	**Of interest**
6 Intermediate physics 10/12	Fluid flow classification Pollution (scalar) transport	ANSYS Fluent – passive scalars Fire Dynamics Simulator – passive scalars Post processing:	7: Plume dispersion	Presentation skills	CFD on the Internet

		GNUPLOT Excel macros Python Automation HTML			
Suggested reading: Computational Fluid Dynamics: A Practical Approach, Chapter 6, Section 6.2 (Chapter 4 in 3rd edition) ANSYS Fluent User Guide – Chapter 6, Chapter 13					
7 Special topics 1 (moving grids) 10/19	Turbulence modeling – large eddy simulation	Fan theory	8: Moving grids – modeling a fan 9: Moving grids – a 3D axial fan		
Suggested reading: ANSYS Fluent User Guide – Chapter 10, ANSYS Fluent Theory Guide – Chapter 2					
8 Special topics 2 (buoyant flows) 10/26	Modeling natural ventilation Fire modeling 1	Buoyant flows and natural ventilation Modeling a fire in ANSYS Fluent	10: Natural ventilation of a shed 11: Fire in a room – Fluent (initial steps)		
Suggested reading: ANSYS Fluent Theory Guide Chapter 5					

CASE STUDIES IN COMPUTATIONAL FLUID DYNAMICS MECE E6104 FALL 2020

Lecture / tutorial	Theory	Practice	Cases	Delivery	Of interest
9 Special topics 2 (buoyant flows) (lecture 8 continued from previous...) 11/2	Continuation from lecture 8...plus topics related to modeling a fire using ANSYS Fluent	Radiation heat transfer in Fluent	11: Fire in a room – Fluent (continued)		
Assignment 4 (issued): TBA Major assignment (issued): TBA (tentative topic – virus/particle dispersion) Suggested reading: ANSYS Fluent User Guide – Chapter 8.3					
10 Recap session 11/9	**Recap session:** Revisit some key concepts and new topics for 2020 (time permitting – tentative outline below)				
	Fire modeling 2	Fire Dynamics Simulator – fires	12: Fire in a room - FDS		Genetic algorithms in FDS
Suggested reading: ANSYS Fluent User Guide – Chapter 14					
11 / 12 Special topics 3 11/16			13: Air quality control 14: Recirculating flows 15: Compressible gas leak		
Quiz (issued): Take home quiz covering topics covered in class					
12 Special topics 3 – continued 11/30			16: Wind loading on a solar panel 17: SpaceClaim and complex geometry		
Take home quiz: Covers materials presented during classes to date Suggested reading: ANSYS Fluent Tutorial Guide Chapter 5 and Chapter 6					

CASE STUDIES IN COMPUTATIONAL FLUID DYNAMICS MECE E6104 FALL 2020

Lecture / tutorial	Theory	Practice	Cases	Delivery	Of interest
13 Special topics 4 12/3		Recap – summary of good practice – NAFEMS	18: Modeling a turbine 19:		Further topics...brief

			Multiphase flow (particles)		overview... Multiphase flow
Suggested reading: ANSYS Fluent Tutorial Guide Chapter 14 and Chapter 15					

CASE STUDIES IN COMPUTATIONAL FLUID DYNAMICS MECE E6104 FALL 2020

Semester Calendar

This is not an official university calendar – students shall consult the official university calendar if in unsure about any dates
Note that dates for assignments / quizzes are approximate and subject to change

Week 1: 9/7 Lecture 1	**Week 7: 10/19** Lecture 7	**Week 13: 11/30** Lecture 12 Quiz due 12/2
Week 2: 9/14 Lecture 2	**Week 8: 10/26** Lecture 8	**Week 14: 12/7** Lecture 13
Week 3: 9/21 Lecture 3 Assignment 1 due 9/25	**Week 9: 11/2 (election day 11/3)** Lecture 9 Assignment 3 due 11/6 Major assignment set 11/2	**Week 15: 12/14** Last day of classes 12/14 No further classes Office hours by appointment / arrangement
Week 4: 9/28 Lecture 4	**Week 10: 11/9** Lecture 10	**Week 16: 12/21** No further classes Office hours by appointment / arrangement Major project due (12/23)
Week 5: 10/5 Lecture 5 Assignment 2 due 10/9	**Week 11: 11/16** Lecture 11 Assignment 4 due 11/20	
Week 6: 10/12 Lecture 6	**Week 12: 11/23 (academic holiday 11/25, Thanksgiving 11/26, holiday 11/27)** Thanksgiving – no class	

MECE E6313 Advanced Heat Transfer

Arvind Narayanaswamy, Department of Mechanical Engineering, Columbia University.

Topics: Review of under-graduate heat transfer (steady-state heat con- duction, thermal resistances, convective heat transfer); introduction to mass transfer; transient heat conduction - separation of variables and laplace trans- form methods; single-phase flow through pipes; external flow over plates - boundary layer theory, similarity transforms, and integral methods; intro- duction to turbulent flows.

Knowledge of coding, preferably in Python, will be essential.

Grading:	Homework	(50%, approximately 5 HomeWorks for the course)
	Mid-term	(25%)
	Final	(25%)

Textbooks: Heat and mass transfer, by Alan F. Mills. A heat transfer textbook, by Lienhard and Lienhard (Dover Publications; pdf copy can be downloaded from Prof Lienhard's website). Heat conduction by Kakac, Yener, and Navierra-Cotta.

Sequence of topics:

Week	Topic
1	Review of undergraduate heat transfer
2	Introduction to mass transfer
3	Mass diffusion and convective mass transfer
4	Transient heat conduction - separation of variables
5	Transient heat conduction - separation of variables and laplace transforms
6	Transient heat conduction - laplace transforms
7	Laminar flow through pipes
8	Laminar flow through pipes and flow or plates
9	Laminar flow over plates - boundary layer method - similarity transforms
10	Boundary layer method - natural convection - similarity transforms
11	Turbulent flows - introduction - law of the wall
12	Turbulent flows - flow through pipes
13	Turbulent flows - flow over flat plates

MECE E6400 – Advanced Machine Dynamics

Spring Semester 2020 – Thursday 7pm-9:30pm – Mudd 627

Professor: Nicolas W. Chbat, PhD

Teaching Assistant: Patricio Torres

	Syllabus	
Section	**Topic**	**Weeks**
I	Newtonian and Euler Dynamics	7
II	D'Alembert, Lagrangian, and Hamiltonian Dynamics	5
III	Stability of Dynamic Systems	2
	Detailed Syllabus	
Week	**Topic**	**Hours**
1,2	Motion Relative to a Rotating Frame	4
2,3,4	Newton-Euler Equations of Motion	7
4,5	Gyroscopic Motion	**4**
6	Rigid Bodies in Free Rotation, Poinsot Construction	**3**
7	Rigid Bodies in Free Rotation	**3**
8	Generalized Coordinates, Constraints, D'Alembert Principle (Virtual Work)	**3**
9,10	Lagrange Equations for Holonomic Systems	**6**
11	Non-holonomic Lagrange Equations, Hamiltonian	**3**
12	Hamilton Equations, Legendre Transformation	**3**
13	Stability of Nonlinear Dynamic Systems (Lyapunov 1st method)	**3**
14	Stability of Nonlinear Dynamic Systems (Lyapunov 2nd method)	**3**
Extra	Lab session: Gyroscope, Free Rigid-Body Rotation	**1 1/2**

Grade:
Homework: 33%
Exam 1: 22%
Exam 2: 45%
Total: 100%

Textbooks (suggested – on reserve in library):

1. **Meirovitch** *Methods of Analytical Dynamics* (suggested – on reserve)

Rationale: Articulating real word dynamics mathematically, i.e. modeling, is often half of the battle in solving engineering problems. Understanding different classical modeling approaches (vectorial and variational mechanics) to solve complex problems is an invaluable tool for the practicing mechanical engineer. These advanced engineering approaches are useful in both industrial and academic settings.

Course: MECEE6422: Intro-Theory of Elasticity I
Meeting Location: 337 Seeley W. Mudd Building
Meeting Time: Tuesday 1:10PM-3:40PM

Instructor Information

Kristin Myers, Associate Professor of Mechanical Engineering
Office: 234 S. W. Mudd
E-mail: kmm2233@columbia.edu
Office Hours: Mondays 1030AM-1200PM, Tuesdays 400PM-500PM, or by appointment

TA

Lei Shi
Office: 245 S. W. Mudd
E-mail: ls3374@columbia.edu
Office Hours: Mondays (in-person in the TA room) 3:30-5:30 and always available via e-mail or discussion board

References:
Recommended Text:

Introduction to continuum mechanics. W. Michael Lai, David Rubin, Erhard Krempl. (https://clio.columbia.edu/catalog/11532925)

Website & Discussion Board Managed through Columbia Courseworks (https://coursework2s.columbia.edu/)

Corequisites: APMA E4200

Course Objectives

Analysis of stress and strain. Formulation of the problem of elastic equilibrium. Torsion and flexure of prismatic bars. Problems in stress concentration, rotating disks, shrink fits, and curved beams; pressure vessels, contact and impact of elastic bodies, thermal stresses, propagation of elastic waves.

Method of Evaluation

Homework	15% In-class
Midterm	35% (OCTOBER 15, 2019) In-class
Final Exam	50% (Scheduled by the registrar Dec 13-20)

Homework Policy

Please work on the homework sets by yourself. Please consult Prof. Myers or the TA before consulting your classmates.

Classroom Policy

Food and drinks are okay, but please do not be disruptive. We will have 1 10-minute around 230.

Copyright notice

I would like to notify all individuals with access to the MECE E6422 course material that the course material for MECE E6422 is copyrighted and is not to be freely distributed/posted online without the written consent of the professor. I explicitly deny consent to the posting of the lecture slides, exams, assignments and answers to any assignment or exam on any website outside of Columbia University's Courseworks. Providing and posting such content is in violation of the Digital Millennium Copyright Act.

Academic Honesty Policies

The following constitutes cheating:

- Copying assignments from others.
- Consulting solutions sets and laboratory reports from previous years.
- Consulting exams from previous years that were not made available by instructor.
- Completing individual assignments in a group, when permission not explicitly granted by instructor.
- Plagiarizing the work of others. **Cheating may lead to the following consequences:**

- Student receives a failing grade for a specific assignment.
- Student receives a failing grade for an entire course.
- Student may be expelled from the university.

Student bill of rights:

- Academic honesty policies clearly explained at start of semester
- Course requirements/grading policies/etc. must be clearly stated at start of semester.
- Textbook/reference book usage must be clarified at start of semester.
- Homework assignments will be graded on a weekly basis (unless clear explanation provided).
- Midterm exams will be graded within two weeks of test (unless clear explanation provided).
- Final exams and/or projects will be graded within the deadlines set by the university.
- Instructor and teaching assistants must provide office hours or otherwise explain procedure for meeting with students.
- Instructors will provide pertinent information on assignments and lab reports in a timely manner.

The academic honesty policies for Columbia College are listed at:
http://www.college.columbia.edu/academics/integrity

MECE E6423 Introduction to the Theory of Elasticity II

Course:	MECE E6423: Introduction to the Theory of Elasticity II
Instructor:	Professor Jeffrey W. Kysar
Office:	244 Mudd Building
Email:	jwkysar@columbia.edu
Telephone:	212-854-7432 Office Hours: Fridays, 9:00 am – 10:00 am, or by appointment
Format:	Weekly 150-minute lecture distributed via Columbia Video Network.
Textbook:	No required textbook, but a detailed reading list will be distributed.
Homework:	Homework sets will be assigned approximately weekly.
Grading:	Several Homework Sets, 75% Final Project, 25%
Description:	Elasticity is the study of reversible deformations of materials. For materials and structures that can be treated by continuum methods, the finite element method is commonly used to calculate the stresses and deformations associated with various applied loads. However, a significant class of problems still defies ready solution with numerical methods because the stresses and strains are formally singular at a material point. In this course, we will concentrate our attention on such singular problems that include point or line loads, dislocations and cracks. In addition, we will consider the stress concentrations associated with various void shapes within an elastic solid. Further we will assume loading configurations that will lead to anti–plane de- formation, plane stress and plane strain, as well as full three–dimensional de- formation. We will develop solutions for both isotropic and also anisotropic elastic solids. In addition, we will introduce and employ path–independent integrals to compute effective configurational forces on the voids and singularities. Although real methods will be used for some problems, the solution methods will be predominantly complex methods including: Analytic continuation method, Hilbert–Riemann problem and Plemelj integral.
Expectations:	Students may freely discuss their work with others, but any work submit- ted for grading must be that of the student and must be representative of the level of understanding of the student. Under no circumstances will the copying of analysis or text from any source be tolerated.

Syllabus

1. Overview of governing equations of Elasticity
   - (a) Equations of equilibrium under infinitesimal strain
   - (b) Constitutive relations for linear elastic behavior
   - (c) Linear strain-displacement relationships
   - (d) Compatibility equations
   - (e) Tensor components described in Cartesian and cylindrical coordinate systems

2. Plane deformation states
   - (a) Anti-plane strain
   - (b) Governing equations of anti-plane strain
   - (c) Plane stress and plane strain
   - (d) Governing equations of plane stress and plane strain

3. Anti-plane strain using real methods
   - (a) Most general solution for harmonic equation with separate radial and circumferential functional dependencies
   - (b) Solution to various anti-plane problems with stress singularities

4. Overview of complex analysis
   - (a) Definition of analytic function
   - (b) Single- and multi-valued functions and branch cuts
   - (c) Laurent series

(d) Identity theorem and Analytic Continuation
(e) Entire functions and Liouville's theorem
(f) Harmonic functions in the complex plane

5. Anti-plane strain using complex methods
    (a) Derive governing equations expressed in terms of complex variables
    (b) Solution to various anti-plane problems with stress singularities
    (c) Superposition of solutions for problems with multiple singularities

6. Conformal mapping in the complex plane
    (a) Derive governing equations for use with conformal mapping
    (b) Derive solution for stress and deformation state around an elliptical void in anti-plane strain

7. Effective forces in defects in elastic materials
    (a) Physical meaning of J-integral, L-integral and M-integral
    (b) Path independent integrals expressed in terms of complex potentials
    (c) Examples to calculate effective forces on defects in anti-plane strain

8. Plane stress and plane strain using complex methods
    (a) Derive governing equations expressed in terms of complex variables
    (b) Solution to various in-plane problems with stress singularities
    (c) Conformal mapping of in-plane problems
    (d) Derive solution for stress and deformation state around an elliptical void for in-plane problems

9. Further overview of complex analysis
    (a) Cauchy Integral Theorem
    (b) Principal Value of non-integrable singular integral
    (c) Cauchy Integral Formula along contours
    (d) Sectionally analytic functions
    (e) Plemelj Formulas
    (f) Jump condition across open contour
    (g) Riemann-Hilbert problem definition
    (h) Solution to homogeneous and heterogeneous Riemann-Hilbert problems
    (i) Application of Riemann-Hilbert problem to solving interfacial crack problems in anti-plane strain

10. Anisotropic elasticity under anti-plane strain conditions
    (a) Review of anisotropic linear elastic constitutive behavior
    (b) Derive conditions under which pure anti-plane deformation is admissible in crystals
    (c) Derive governing equations for anti-plane strain in anisotropic linear elastic materials
    (d) Solution of various problems involving singularities in anisotropic linear elastic materials

MEEM E6432 Small Scale Mechanical Behavior

Course:	MEEM E6432: Small Scale Mechanical Behavior
Instructor:	Professor Jeffrey W. Kysar
Office:	244 Mudd Building
Email:	jwkysar@columbia.edu
Telephone:	212-854-7432
Office Hours:	Fridays, 9:00 am – 10:00 am, or by appointment

Format: Weekly 150-minute lecture distributed via Columbia Video Network.

Textbook: No required textbook, but a detailed reading list will be distributed.

Homework: Homework sets will be assigned approximately weekly.

Grading: Several Homework Sets, 75%
Final Project, 25%

Description: Introduction to the mechanical behavior of small-scale components, structures and devices. It is common that the governing equations for such small systems are non-linear, either due to a non-linear relationship between dis- placement and strain or a non-linear relationship between strain and stress, or both. The Calculus of Variations is used as a means to derive the governing equations of beam and plate theory that account for the non-linearities. This will lead to detailed discussions of the deformation and vibration of beams and plates, to the stress, deformation, and substrate curvature in thin films, as well as fracture, delamination, bulging, buckling and of thin films. The thermodynamics of solids will be reviewed, which will provide the basis for a detailed discussion of non-linear elastic behavior as well as the study of the equilibrium and stability of surfaces.

Expectations: Students may freely discuss their work with others, but any work submitted for grading must be that of the student and must be representative of the level of understanding of the student. Under no circumstances will the copying of analysis or text from any source be tolerated.

Syllabus

1. Overview of governing equations to solve problems of mechanical deformation
   - (a) No previous experience with Elasticity will be required for this course

2. Overview of variational calculus with applications to
   - (a) Nonlinear beam theory
   - (b) Nonlinear plate theory

3. Stresses in thin films
   - (a) Measurement of stresses in thin films
   - (b) Wafer curvature and Stoney equation
   - (c) Stresses due to different deposition processes

4. Overview of fracture mechanics
   - (a) Classification of different types of crack and fracture behaviors
   - (b) Singular stress state at crack tip
   - (c) Energy release rate upon crack advance and fracture criterion

5. Delamination and fracture in thin films
   - (a) Morphologies of fracture
   - (b) Energy release rates and fracture criterion

6. Thermodynamics of deformed solids
   - (a) Free energies
   - (b) Thermodynamic definition of elastic properties
   - (c) Elastic properties under isothermal and adiabatic conditions
   - (d) Calculation of elastic properties from atomic potentials
   - (e) Linear and non-linear elastic properties

7. Mechanics of two-dimensional materials

(a) Linear and non-linear elastic properties

(b) Mechanical characterization

MECE E6617 Advanced Kinematics, Dynamics, and Control in Robotics

Summary of the course:
Advanced topics in robotics using fundamentals of kinematics, dynamics, and control. Topics covered include: Characterization of Orientation and angular velocity of rigid bodies, Kinematic Solutions of Planar Mechanisms, Dynamics of Closed Chains and Free-floating Bodies, Gravity Balancing of Mechanisms, Dynamics and Dependence on Inertia Redistribution, Under-actuation Systems, Feedback Linearization of SISO systems, Feedback Linearization of MIMO Systems, Design of Under-actuated Open-Chain Robots, Parallel-Actuated Robots.

Prerequisites: Course on linear and/or nonlinear control theory, Introduction to Robotics, or Permission of the instructor

Notes: The course was taught as experimental class in Spring 2016, 2017, 2019.

Instructor: Sunil K. Agrawal, Ph.D.
Professor of Mechanical Engg./Rehabilitation and Regenerative Medicine
Office: 230 Mudd Hall
Email: Sunil.Agrawal@Columbia.edu

Textbook: Lecture materials will be based on Papers/Book chapters etc.

Prerequisites: MECEE 4602 or Instructor's Permission

Schedule:

1/28	Characterization of Orientation and angular velocity of rigid bodies
2/4	No Class: Work on Technical Paper review from ICRA papers
2/11	Kinematic Solutions of Planar Mechanisms
2/18	Kinematic Solutions of Spring-loaded Planar Mechanisms
2/25	Dynamics of Closed Chains and Free-floating Bodies
3/4	Gravity Balancing of Mechanisms
3/11	Dynamics and Inertia Redistribution
3/25	**Mid-Term Project Presentation** - Design of Gravity Balanced Systems
4/1	Under-actuation Systems, Feedback Linearization, SISO systems
4/8	Feedback Linearizability: MIMO Systems
4/15	Design of Under-actuated Open-Chain Robots
4/22	Parallel-Actuated Robots
4/29	Lower Degree-of-freedom Parallel Actuated Robots
5/6	**Final Project Presentation**

Grading:

Homework:	20%
Technical Paper Review	10%
Mid-Term Project:	20% (Includes presentation/Technical report)
Final Project	50% (Includes presentation/Technical report)

Other Course Details:

(i) **Homework** will be assigned after the completion of a topic. These will be due in a week after the assigned date. The problems will require programing, simulation, and animation using MATLAB. There will be 8 homework.

(ii) **Technical Paper Review**: These will be performed in assigned groups of 2. You choose a paper from ICRA 2010-2018 Proceedings involving topics of ‘kinematics’, ‘dynamics’, ‘closed-chain mechanisms’, ‘under-actuation’, or other closely-related topics. Please inform and obtain permission from Instructor/TA to work on it. Prepare 6 PowerPoint slides that include the following: Problem statement, Prior research, Solution approach, Results, Conclusions and Future Extensions.

(iii) **Mid-Term Project**: The students will work in assigned groups of 2. Review the literature on gravity balancing and define a mechanism that you will like to design which is gravity balanced. Motivate this system from a practical application, e.g., human wearables, industrial. Please discuss your project with the Instructor/TA.

Perform the scientific analysis that will validate your design. Prepare 6 PowerPoint slides that include the following: Problem statement, Your solution approach, Results, Conclusions and Future Extensions. Write a 3-page technical report in word (2 column 10 point) using the typical format of ICRA paper.

(iv) **Final Project**: The students will work in self-selected groups of 2. Define a problem that involves novel design, analysis, simulation, etc. using the principles that you have studied in this course. The problem should have a good motivation and should be approved by the Instructor/TA.

Presentation - Prepare 6 PowerPoint slides that include the following: Problem statement, Your solution approach, Results, Conclusions and Future Extensions. *Technical Paper* - Write a 4-page technical report in word (2 column 10 point) using the typical format of ICRA paper.

(v) **Course Ethics**: Discussion of the lecture material among students is encouraged.
However, home-works must be performed individually.

E6620 Applied Signal Recognition and Classification

Instructor: Prof. Homayoon Beigi <beigi@recotechnologies.com> (hb87@columbia.edu)

Textbook: H. Beigi, "Fundamentals of Speaker Recognition," Springer, New York 2011.

Grading:

Homework (20%):
- Implementation of a speech recognition engine using the VoxCeleb2 example of Kaldi or Yolov3 of Darknet

- Creation of a Flowchart with a paragraph for each block in the flowchart, describing the whole Machine Learning Process above.

- Results of the decoding.

Midterm Proposal (20%):
15% - 2-page extended abstract describing the results and proposing modifications to one specific part of the engine to increase performance (accuracy, speed, or both)
5% - 5-10-minute presentation of the above.

Final Project (60%):
45% - 6-page IEEE conference style paper describing the system and results obtained from the modification. Discussion and Implementation of an Improvement in one of the aspects of the speech recognition engine.

10% - Code and Results.

5% - 5-minute presentation of the results.

Course Description:

Applied Signal Recognition is a comprehensive course, covering all aspects of Signal Recognition from theory to practice. In this course such topics as Time and Spatial Signals (such as Audio, Image, and Vibration signals) Signal Representation, Signal Processing and Feature Extraction, Probability Theory and Statistics, Information Theory, Metrics and Divergences, Decision Theory, Parameter Estimation, Clustering and Learning, Transformation, Hidden Markov Modeling, Search Techniques, Deep Neural Networks, Support Vector Machines and other recent machine learning techniques used in signal recognition are covered in some detail. Also, applications in Machine and Structural Health analysis/prognosis, Objection Detection and Recognition, Audio Event Detection, Multimodal analysis, Image Recognition, Video Analysis are covered in detail.

Also, several open source software packages are introduced, with detailed hands-on projects using Kaldi, Darknet, and/or Caffe to produce a fully functional signal recognition engine. The lectures cover the theoretical aspects as well as practical coding techniques. The course is graded based on a project. The Midterm (40% of the grade) is in the form of a two-page proposal for the project and the final (60% of the grade) is an oral presentation of the project plus a 6-page conference style paper describing the results of the research project. The instructor uses his own Textbook for the course, Homayoon Beigi, "Fundamentals of Speaker Recognition," Springer-Verlag, New York, 2011. Every week, the slides of the lecture are made available to the students.

Research Projects:

Individual projects are done using Kaldi or Darknet, depending on the topic of interest, and picked from topics of interest to the students such as,
- Machine health prognosis and monitoring
- Structural health monitoring
- Acoustic processes
- Vibration analysis
- Sequence-to-sequence modeling
- Image processing ...

Lectures:

Week 1

Introduction (Overview of Signal Recognition and its history)
Structural health monitoring, Audio, Image, Vibration, Brain-Wave, and applications including human biometrics, imaging, geophysics, machinery, electronics, networking, sequence modeling, communications, and finance

Week 2

Signal Representation of time-dependent signals
Sampling, Quantization and Amplitude Errors
Practical Sampling and Associated Errors

Week 3

Fundamentals of Signal Processing
The Sampling Process
Spectral Analysis and Direct Method Features

Weeks 4 & 5

Signal Processing of Speech and Feature Extraction
Auditory Perception Linear Predictive Cepstral Coefficients (LPCC) Perceptual
Linear Predictive (PLP) Analysis
Alternative Cepstral-Based Features
Other Features
Signal Enhancement and Pre-Processing

Week 6

Decision Theory
Hypothesis Testing
Bayesian Decision
Theory Bayesian Classifier Decision Trees

Parameter Estimation

Maximum Likelihood Estimation (MLE, MLLR, fMLLR)
Maximum A-Posteriori (MAP) Estimation
Maximum Entropy Estimation
Minimum Relative Entropy Estimation
Maximum Mutual Information Estimation (MMIE)
Model Selection (AIC and BIC)

Weeks 7, 8, & half of 9

Neural Networks
Perceptron
Feedforward Networks
Time-Delay Neural Networks (TDNN)
Convolutional Neural Networks (CNN)
Recurrent Neural Networks (RNN)
Long-Short Term Memory Networks (LSTM)
End-to-End Sequence (Encoder/Decoder) Neural Networks
Embeddings and Transfer Learning

Weeks second half of 9 & 10

Probability Theory and Statistics
Measure Theory
Probability Measure
Integration
Functions
Statistical Moments
Discrete and continuous Random Variables
Moment Estimation

Multi-Variate Normal Distribution

Sequence Modeling
Further use of CNNs, RNNs, and TDNNs
Finite State Transducers

Week 11

Unsupervised Clustering and Learning
Vector Quantization (VQ)
Basic Clustering Techniques
Estimation using Incomplete Data

Transformation
Principal Component Analysis (PCA)
Linear Discriminant Analysis (LDA)
Factor Analysis (FA)
Probabilistic Linear Discriminant Analysis (PLDA)

Week 12

Information Theory
Sources
The Relation between Uncertainty and Choice
Discrete Sources
Discrete Channels
Continuous Sources
Relative Entropy
Fisher Information
Metrics and Divergences

Hidden Markov Modeling (HMM)
Memoryless Models
Discrete Markov Chains
Markov Models
Hidden Markov Models
Model Design and States
Training and Decoding
Gaussian Mixture Models (GMM)
Practical Issues

MEIE E4810 Intro to Human Space Flight

Spring 2020

Course Description:

Introduction to human spaceflight from a systems engineering perspective. Historical and current space programs and spacecraft. Motivation, cost and rationale for human space exploration. Overview of space environment needed to sustain human life and health, including physiological and psychological concerns in space habitat. Astronaut selection and training processes, spacewalking, robotics, mission operations, and future program directions. Systems integration for successful operation of a spacecraft. Highlights from current events and space research, Space Shuttle, Hubble Space Telescope, and International Space Station (ISS). Includes a design project.

Prerequisties:
Junior standing and permission of instructor

Text:

- Harrison, A., "*Spacefaring - The Human Dimension*", University of California Press, Los Angeles, CA, 2001. (available online at Columbia University Libraries)

Reference Material:

- Massimino, "*Spaceman – An Astronauts Unlikely Journey to Unlock the Secrets of the Universe*", Crown, New York, 2016.
- United Space Alliance, LLC., *Shuttle Crew Operations Manual*, OI-33, NASA, Document Number USA007587. Available for free on-line: http://www.nasa.gov/centers/johnson/pdf/390651main_shuttle_crew_operations_manual.pdf
- International Space Station Flight Controller Console Handbooks. Available for free online at: https://isslive.com/handbooks/
- Mission Operations Directorate Space Flight Training Division NASA Johnson Space Center, *International Space Station Familiarization*. Available for free online at: http://www.spaceref.com/iss/ops/iss.familiarization.pdf

Course Objectives:

- Understand how astronauts, engineers, and scientists approach the human exploration of space.
- Understand how various spacecraft systems work together for successful space missions.
- Understand how the unique characteristics of the space environment affects astronauts and space systems requirements.
- Complete a class design project.

Grades:

- Homework: 40%
- Project: 50%
- Peer Review, Class Participation, Attitude: 10%

Homework & Reading Assignments:
Homework and reading assignments will be assigned on most of the weeks during the semester. The homework will be done by each student individually. The objective of the homework will be to re-enforce material covered in class and in the reading assignments.

Project:
Students will work in teams of four or five. Design project topic will be the chosen and developed by each group. It can be based on any of the topics covered throughout the semester or it can be a topic not covered in class that the group is interested in pursuing. The project will have graded milestones throughout the semester with the appropriate product, final report, and group presentation due at the end of the semester.

MECE E4214MEMS Production and Packaging

Course Material:
MEMS Production and Packaging will cover a wide variety of practical issues encountered in the manufacturing of a packaged MEMS transducer. The class will begin with an extension of the undergraduate MEMS curriculum with a lecture on Microfluidics and BioMEMS and will then rapidly transition to MEMS Packaging and Production. Our course will begin with a detailed study of analog instrumentation, then transition to using this information to understand the design of MEMS Packaging. Throughout this analysis, the impact of design and Packaging on the Production of MEMS devices will also be discussed. The class will be heavily influenced by the production of one of the first, most common MEMS transducers: the piezoresistive pressure sensor. Time permitting, we will cover related topics including materials science issues particular to semiconductors, project management for production, modeling and process control examples, and others. Each topic will be discussed in the context of MEMS transducer design and how manufacturing choices ultimately impact performance. Based on the coursework, students will develop a written project either individually or in groups that solves a key issue in MEMS Packaging applications.

The student will be assumed to have an undergraduate level understanding of materials science and control theory that would be covered in a typical Mechanical or Electrical Engineering curriculum.

Course Objective:
The objective of the course is to prepare students for practical MEMS design in the private sector. Examples of end-use applications will be explored to illuminate how behavior in the field dictates design. Some of these design choices will then be explored from a design and manufacturing point of view. At the end of the course, students will be prepared to use MEMS transducers, diagnose problems, and relate the performance of transducers to their design and manufacturing.

Week	Topic
1	Introduction, Microfluidics, BioMEMS
2	Transducer Packaging Design Overview
3	The Transducer Signal Chain – Analog to Digital Conversion
4	The Transducer Signal Chain – Amplification, Filtering
5	The Transducer Signal Chain – Noise Sources and Cabling
6	The Transducer Signal Chain – Strain Gages, Wheatstone Bridges
7	Comparative Packaging: Capacitive Sensors
8	Comparative Packaging: Piezoresistive Sensors
9	Comparative Packaging: Piezoelectric Sensors
10	Guest Lectures: MEMS Business: Export Control, Project Management
11	Materials Science for Advanced MEMS Packaging
12	Materials Science for Advanced MEMS Packaging
13	Materials Science for Advanced MEMS Packaging

Grading
40% Class Participation
40% Homework
20% Exams

Expectations:
Attendance is mandatory, as class participation is a critical element of the curriculum. Students will be expected to arrive for each lecture on time and participate in the discussion. Discussion topics may be posted to Courseworks, students will be expected to participate with these discussions as well. Readings will mostly consist of research papers relating to MEMS fabrication, with the occasional book chapter where appropriate. Readings will be assigned prior to the week's lecture and students will be expected to come to class prepared to discuss assigned readings in the context of that day's lecture material. Homeworks will be assigned throughout the semester and the penalty for late homeworks will 10% of the total grade for that assignment per day late.

Course Materials:
TBD