AC 2010-1903: A SPIRAL LEARNING CURRICULUM IN MECHANICAL ENGINEERING

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A SPIRAL Learning Curriculum in Mechanical Engineering

Abstract

In this course development project funded through an NSF CCLI Grant, we are developing, implementing, and evaluating a new required integrated four-course sequence taught in the first two years of our ME curriculum. Each year will focus on a broad contemporary topic in Mechanical Engineering, namely robotic/mechatronic systems and sustainable energy systems. Using these themes we will introduce students to: the fundamentals of multiple engineering science topics, design practice and methodology, and the knowledge and skills required in professional engineering practice—all of which will be reinforced in, and expanded upon, in later more specialized courses. This new sequence attempts: 1) to address the well-publicized challenges of educating the current generation of American students with their short attention spans, expectations of immediate rewards, and limited "hands-on" experience (vs. years of "fingers-on" experience with modern electronic devices), 2) to improve our graduates' professional skills as recommended by practicing engineers, and 3) to implement improved pedagogical techniques via an overriding "design as knowledge" teaching philosophy[1] that will teach through an emphasis on model-based design and product realization in a Student-driven Pedagogy of Integrated, Reinforced, Active Learning (SPIRAL) approach. That approach applies Bruner's concept[2] of a "'spiral curriculum' that turns back on itself at higher levels" through repetition at ever increasing depths of knowledge. Our approach thus both *distributes* the teaching of basic engineering knowledge and skills through multiple courses and *integrates* their teaching throughout the curriculum via repetitive exposure in multiple courses, using multiple active learning approaches. This paper outlines our overall approach and philosophy, while three companion papers describe our initial experiences in the first course in this four-course sequence.

1. Introduction

As shown in many individual studies and summarized in recent articles and books,[3-6] when compared to traditional lecture courses, the use of active, co-operative learning and open-ended projects seems to: significantly enhance learning, retention and application of material; help non-traditional students in their learning; and motivate engineering students to remain in school. Many departments have successfully implemented subsets of the possible approaches (e.g., Fig. 1) in individual courses.

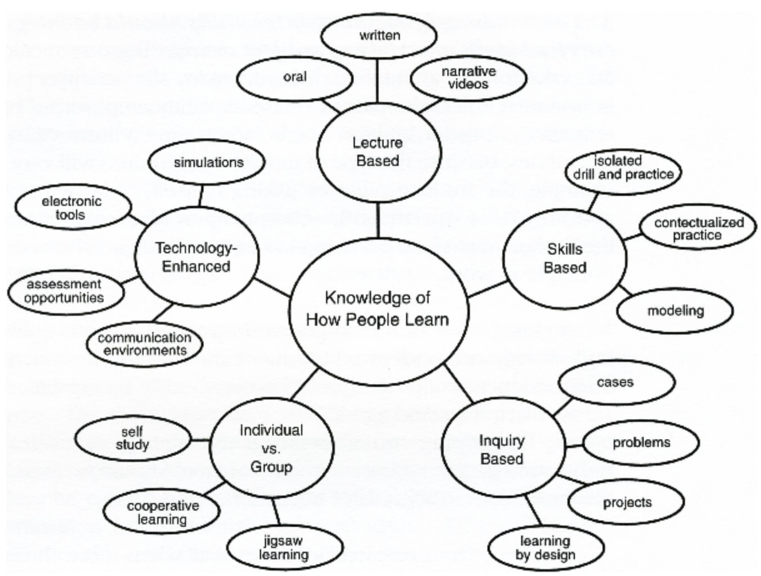

Figure 1. How people learn.[5]

We propose to make a major step towards an extended and integrated use of these techniques by moving from their isolated use in individual courses into a SPIRAL curriculum that uses active, co-operative, design-based learning approaches in four new sequential coordinated lower division courses. These courses are also integrated with our students' required existing upper division active learning courses (see Table 1). Each newly transformed (from four existing courses) course will: 1) have a primary technical and computational emphasis; and 2) use an open-ended, collaborative learning-based design project as a vehicle to teach that material. In turn, each project will require 1) use of an in-depth model-based design approach that applies the technical emphasis material, 2) the learning and application (in the final design project) of new manufacturing, actuator, machine element and instrumentation skills, 3) the learning and application of new professionalism skills, and 4) the reinforcement and extension of material learned in previous courses. This integration will result in repeated use of project-based design, analysis, and professional skills from day one to graduation. Students will work on a design project each semester of their undergraduate education: one project in each of the four new courses during the freshman and sophomore years; the year-long design of an autonomous robot in existing Mechatronics I and II courses; and the year-long senior capstone project. These projects provide a natural vehicle to teach multiple engineering skills in a structured environment by requiring students to design and build physical devices that are evaluated by customers.

Table 1. The Four New Yrs 1 and 2 SPIRAL Classes and the Related Existing Yrs 3 and 4 Active Learning Classes.

Yr	Fall	Spring
1	**Introduction to the Design of Robotic Systems I (ME 1000)** Design Methodology, Spreadsheet Tools	**Introduction to the Design of Robotic Systems II (ME 1010)** Model-Based Design, MATLAB®
2	**Introduction to the Design of Sustainable Energy Systems I (ME 2500)** Numerical Methods, C++	**Introduction to the Design of Sustainable Energy Systems II (ME 2510)** Thermodynamics, EES®
3	**Mechatronics I (ME 3200)** Mechanisms, Sensors, Electronics	**Mechatronics II (ME 3210)** Modeling, Control Systems
4	**Engineering Design I (ME 4000)** Capstone Design Course	**Engineering Design II (ME 4010)** Capstone Design Course

1.1 Specific Objectives

Our goal is to have our students become proficient in:

Model-based design skills. A primary goal of these new courses is to teach the students the skills needed to develop, apply and evaluate the predictions of engineering models during the design, manufacturing and testing of real devices. Within each course the students will learn and integrate the modeling, mathematical, experimental, programming, manufacturing and statistical analysis techniques needed to complete the course project. This learning will proceed in a coordinated, structured manner through the combined use of lectures, labs and design projects. We have done this in our existing ME 1000 course for several years, where emphasis has been on the correct combination of appropriate analysis and experimentation in design.

Professional engineering skills. The following will be introduced and emphasized starting in ME 1000 so that, with reinforcement throughout the four-year curriculum, our students will be well-prepared to enter the engineering work force.

Design methodology. Required design projects continually improve our students' ability to manage and complete engineering projects, including the skills of problem definition, creativity, appropriate analysis, decision making, project organization, system integration, follow through to construction and completion, economic considerations, design under uncertainty, testing and evaluation.

Communication and teamwork. Design projects are excellent vehicles with which to teach these skills since such projects involve the natural assignments of proposals, memos, design reviews, final reports, and co-operative learning.

Social, ethical and environmental concerns. Design projects and related lecture case studies will be chosen to naturally involve these issues so that students must address them in their designs, written and oral presentations, and associated homework.

Thinking skills. Teaching the above technical and professional skills will progress from the simple to the more complex, following Bloom's taxonomy[7] to produce critically thinking engineers. Indeed, the best description of our long range goal has been stated as:[4] "If all that is done, most of the students who are capable of functioning at the high levels (of Bloom's taxonomy) would be able to do so—and if engineering instructors collectively do it in every engineering course from the freshman through the senior year, our graduates will come out able to do the modeling, design, and critical and creative thinking at a level that we can barely imagine now."

2. Overview of New Course Sequence

The core of our program is a four-course sequence in the first and second years of our ME curriculum, with the courses having the following characteristics. First, each course will have a primary technical emphasis and will have model-based design and product realization as a unifying motivational theme. The successive emphases are: 1) design methodology and spreadsheet tools, 2) MATLAB® programming, 3) numerical methods, and 4) thermodynamics. Secondarily, within each computationally-intensive course there will be an underlying physics emphasis that will both provide the basis for the model-based design approach and an introduction to the engineering science material they will learn in depth in later courses, and will provide the students with a "contextualized" introduction to the computerized tools being taught. The underlying physics concepts will be the math and technology associated with, sequentially: 1) Newton's and Faraday's laws as applied to Cartesian particle dynamics, plus an introduction to elasticity, 2) the same concepts extended to rotational systems, 3) fluid dynamics, and 4) conservation of energy and heat transfer. Teaching of the fundamental technical and physics emphases will be done through lectures, and their application will occur in the team-based design projects. Laboratories will be used to teach about, test and characterize the mechanical and electrical devices associated with the physics emphasis, and to teach the associated software packages and manufacturing techniques to be used in modeling and constructing the student designs.

2.1 Design Projects

Sample design projects for each of the four new courses are outlined in Table 2. In ME 1000, for example, teams (four students per team) are treated as subcontractors (with company names and logos) to a major educational equipment supply company. That contracting company is looking for a creative new product that teaches the basic principles of Newton's laws by using the newest technologies and web-based resources available for use in lower socio-economic area high schools (this could thus be a service learning project). The subcontractors' goal is to develop a fun, inexpensive, safe, environmentally responsible educational kit, including instructions, to demonstrate the first semester's math, physics and technology emphases. At the beginning of the semester we bring in multiple stakeholders (representatives from the company, i.e., the course instructor and the TAs, plus the end user—local high school students and their physics teachers) to gather information for the teams' problem definitions. At the end of the semester the subcontractors compete with their devices on our department's Design Day, with each student required to design, build, and characterize (model) their device. Students are taught how to be economical and sustainable in their designs through teaching "design for manufacturing" and "design for disassembly." Total life cycle costs are a major consideration. Financial analysis of the project costs starts with simple listings of material costs in the first course, adding sophistication in subsequent semesters, and ending with full, detailed cost accounting in the capstone design sequence.

Table 2. Sample Design Projects and Case Studies.

Course	Team-Based Design Projects	In-Class Case Studies
ME 1000 (Cartesian Motion, Elasticity)	Design an inexpensive educational system that illustrates Newton's second law for high school students, plus an associated educational manual. The device must employ a linear spring, a solenoid and a linear potentiometer.	A circus has asked you to design a method of shooting an elephant to the top of the big top with a spring (a new attraction to complement the "man shot from cannon" act). Design the spring, analyze the dynamics (positions, velocities and "g" forces on the elephant) and discuss the ethical issues involved.
ME 1010 (Rotational Motion)	Design a DC motor-driven cart that demonstrates the principle of automotive safety for drivers ed classes. The cart should be able to show how and why "rollover" occurs.	The National Park Service has requested a design of a human-powered washing machine. Compare your design to the use of a solar-powered, motor-driven system.
ME 2500 (Fluid Dynamics)	Design and build a model, wave-powered electricity generator. Include an analysis of efficiency.	Design an economical, efficient wind turbine system for home use in a NIMBY-sensitive neighborhood.
ME 2510 (Thermal and Energy Systems)	Design an inexpensive solar-powered "crockpot" with a temperature control system so that the system does not overheat when unattended.	A medical volunteer organization has asked you to design a solar-powered vaccine preservation system for use in remote tropical environments.

As the semester progresses, the students are required to systematically progress through the design methodology sequence outlined in Dym and Little:[8] problem statement, objectives list, objectives tree, etc., and periodically report on their progress via eight written reports (six are short memos) to give feedback to the customer. The written and oral reports are graded separately by the course instructors (ME faculty) and Communication instructors—who are provided through our college-wide "CLEAR" (Communication, Leadership, Education And Research) Program. Two major reports are required. First, the students present their proposed design ideas in a mid-term oral and written design review session (taped and reviewed with the communication instructors), and second there is a similar assignment for their final report. In their final report to the contractor the teams are required to: draw their final devices in SolidWorks® (including engineering drawings); show their experimental results for each final device and compare those results to those from calculations using mathematical models of their devices (e.g., in the first semester they might have to throw an egg and use the explicit FD approach to predict the resultant motion of the egg using Newton's laws). The contracting company requires such engineering analysis of all designs in order to evaluate the system performance, for archival documentation, and for possible later scaling and modification of the submitted designs. Discussions of differences between performance and predictions are required. Students are also required to perform self- and team evaluations to evaluate the quality and performance of the devices/team, and make suggestions for design/teamwork improvements.

2.2 Course Lectures, Laboratories and Assignments

Laboratories and lectures are scheduled so that the students obtain the needed skills for their design projects following the principles of "Guided Design."[9] Lectures and associated homework are used to teach the engineering, science and math concepts needed for the design projects. These materials are then used to explain the math and physics behind the tools available in, and limitations of, commercial packages, and to illustrate complex programming concepts. The case studies are chosen to involve the same physics and programming tools that the students will need to analyze and model their design project's performance (see Table 2). The associated lectures treat the case study as a design project, going step by step through the decision-making process and introducing new material as needed by each project. Lectures will involve active learning as much as possible, e.g. 1) a team-based activity using the USAF aircraft crash example to show the difference between decision-making styles;[10] and 2) use of water-filled containers to measure spring constants, discuss the basics of the MKS unit system, emphasize the difference between weight and mass, illustrate statistical principles by showing how one batch of "identical" springs gives a variety of spring constants, and how such uncertainty must be accounted for in their design decisions. Laboratories are used for 1) programming language instruction and instruction in commercial programs (e.g., SolidWorks®, Working Model®) that can be learned without formal lectures, 2) building and characterizing the basic engineering components required for use in their design projects (e.g., gears), and 3) learning the needed manufacturing and assembly skills and processes.

Multiple "menu items" are distributed throughout each of these four courses, with the result that in each course students must "parallel process" several subjects. Table 3 provides an example implementation of this complex organizational task. As much as possible, the timing of teaching the "items" within each course will be "just in time" for the students' projects, while the contents of each course will be selected to be coordinated with the students' other required courses. Subsequent lower and upper division courses will build on and utilize the material taught in these four lower division courses.

Table 3. Examples of Possible SPIRAL "Parallel Processing" Topics and their Distribution throughout the Four New Courses.

Topic/Semester	ME 1000	ME 1010	ME 2500	ME 2510
Primary Theme	Design Methodology; Spreadsheets	MATLAB® Programming	C++ Programming	Numerical Methods
Engineering Science Theme	Newton's Laws for Linear Motion; Elasticity	Rotational Motion	Fluid Dynamics	Thermodynamics and Heat Transfer
Professional Emphasis	Sustainability	Ethics	Economics	Project Management
Communications Theme	Oral and Written Presentations	Teamwork; Decision Making	Conflict Resolution	Technical Leadership
Physics Concepts	F=ma ; Faraday's Laws; Elasticity;	T=Iα ; Faraday's Laws; Fatigue	Drag Coefficient; Friction Factor; Bernoulli's Eqn.	Cons. of Energy; Heat Transfer Modes
Actuators	Solenoids; Linear Motors	Permanent Magnet DC Motors; Torsion Springs	Servo Motors; Pneumatics; Hydraulic Actuators	Thermoelectrics; Solar Cells; Stepper Motors; AC Motors
Sensors	LVDTs; Linear Potentiometers	Accelerometers; Optical Encoders; Tachometers	Pressure Sensors; Flow Meters	Thermocouples; Thermistors; Infrared Sensors
Mechanical Hardware	Springs; Linear Bearings; Linear Actuators	Fourbars; Spur Gears; Bearings	Planetary Gears; Chains; Belts; Fasteners	Worm Gears; Power Screws
Electrical Hardware	R, L, C Elements	Transistors	Op Amps	AC power
Electronic Concepts	Circuits; Ohm's Law	A/D; PWM	Noise; Filtering	Microcontrollers
Software Packages	SolidWorks®	Working Model®	LabVIEW®	COSMOS®
Programming	Excel®	MATLAB®	C++	TK Solver®; EES®
Modeling application or Numerical Method	Graphing; Least Squares Fitting; Numerical Differencing; Explicit FDs	Roots of Equations; Statistics; Numerical Integration	Simultaneous Linear Equations; ODEs; Implicit FDs	Non-linear Equations; PDEs; Experimental Design
Manufacturing Tools (Manual)	Shop Safety; Hand Tools; Drills; Feeds and Speeds	Lathe (intro); Mill (intro)	Lathe(advanced); Mill (advanced)	Vacuum Forming
Automated Manufacturing Tools	Waterjet Cutter	Microfab (MEMS accelerometer)	NC Router	NC Milling; Injection Molding

3. Expected Significance

Students are expected to learn and demonstrate mastery of a variety of engineering skills, thus coming away from the new classes with the ability to:

- Appropriately develop, utilize and evaluate models of engineering systems.

- Appropriately apply the physics emphasis material.

- Critically evaluate the relative roles, strengths, weaknesses, and applications of mathematical models and experiments in solving engineering problems.

- Design engineering systems—including identifying and overcoming the practical difficulties encountered when attempting to design and manufacture a high quality product—and develop and follow a well-planned design methodology.

- Identify and apply the appropriate engineering hardware, methods of analysis, and presentation of experimental results, and to interpret measures of statistical significance.

The following outcomes are also anticipated:

- Increased motivation for learning by developing an early understanding of "the big picture," achieved by providing real examples of how math, physics, and engineering concepts are applied and used, and by showing how engineering serves society.

- Avoidance of the typical "freshman/sophomore myopia" questions, e.g.: "Why am I learning about electricity, I'm an M.E.?" "Why do I need to learn to program 'hangman'?" etc. Instead, the students will learn the (mechanical) engineering value of such subjects beginning on day one.

- Improved preparation for advanced courses, leading to improvement in the content of those advanced classes, thereby further increasing the quality and extent of learning in the junior and senior years.

- Improved learning environment for students with a wide variety of learning styles via the multi-modality teaching approach.

- Improved appreciation for the professional, social, ethical, and environmental aspects of engineering through emphasis on these topics in the design projects and case studies.

- Incorporation of service learning into the curriculum in a natural manner, allowing us to increase our outreach to recruit more diverse and better students.

- Enhanced retention of both traditional and non-traditional students.

Finally, the proposed approach is quite exportable to other Mechanical Engineering Departments, and with modifications, to other engineering disciplines, and can be a model for a common core curriculum.

4. Individual Courses

The four new courses we are developing are:

4.1 Semester 1: Introduction to the Design of Robotic Systems I (ME 1000)

The unifying course emphases are engineering spreadsheet calculations and the physics, math, and technology associated with Newton's and Faraday's laws as applied to Cartesian motion, plus an introduction to the concept of elasticity. The associated educational modules are detailed in Table 4.

Table 4. ME 1000 Lecture and Laboratory Modules.

Lectures (28)	Modules
4	**Primary theme:** Design methodology, spreadsheets
4	**Engineering science theme:** Linear motion (velocity, acceleration, weight, mass, Newton's laws)
2	**Design/professionalism emphasis:** Safety
3	**Communications theme:** Oral and written presentations
4	**Numerical methods**: Graphing, least squares, numerical differencing, explicit finite difference
2	**Mechanical hardware:** Springs, linear bearings, linear motors
6	**Electrical hardware:** Resistance, capacitance, inductance, basic circuits, solenoids, relays, Faraday's laws
1	**Sensors:** Linear pots, LVDTs
1	**Manufacturing:** Waterjet cutter, hand tools
1	**Other:** Visual thinking, hand drawing

Labs (14)	Modules
5	**Engineering software:** SolidWorks®
2	**Engineering software:** Working Model®
2	**Mechanical hardware:** Springs (build and characterize)
1	**Electrical hardware:** UMEB (assemble and test, part 1)
1	**Electrical hardware:** Solenoids (build and characterize)
1	**Electrical hardware:** LVDTs (build and characterize)
2	**Manufacturing:** Safety, hand tools, drilling, feeds and speeds

Design Project. In the past, we have used the design of a spring-powered "egg-zooka" to shoot eggs upward, which captivates the students' attention and brings the math to life. Such a device can be easily built and tested. The test results can then be compared to $F = ma$ predictions of the students' finite difference spreadsheet models and to the predictions of the Working Model® software package. This gives us the opportunity to begin to explain the basic numerical and physical principles behind such packages, and what limitations they have, giving the students the knowledge needed to think critically about such packages—rather than viewing them as unimpeachable black boxes. This example could be expanded on in the new ME 1000 course so that the students would design, build and characterize their springs, which would be used to shoot an egg into a target (e.g., frying pans). The project would require the use of linear springs, solenoids, LVDTs, and an in-house computer board used for sensing and actuator control (the Utah Mechanical Engineering Board, or "UMEB"). The solenoids would be used to pull the springs the needed distance, while the calibrated LVDTs would measure the spring deflection so that they could deactivate the solenoid and thus "shoot" the egg when the spring has traveled the appropriate distance; the required distance would only be announced when the students arrive for the final competition. The solenoid and LVDT would be interfaced with the UMEB to co-ordinate and control the egg-shooting process. Designs would be evaluated on how well they meet the metrics set out by the subcontractor early in the semester, including the accuracy of the egg-shooting. Engineering modeling would be strongly emphasized by requiring mathematical models of all important processes and devices involved in the design ($F = ma$ for the eggs, $F = kx$ for the springs, $V = f(x)$ for the LVDT and $F = f(x)$ for the solenoid). Each student would be required to design, build, and test their spring, solenoid, LVDT, UMEB and overall "egg-zooka" performance.

Lectures. Lectures will be on subjects needed for the students to complete their design projects, including design methodology, engineering science and programming/numerical methods. Simple in-class demonstrations of basic principles will be performed to demonstrate physical principles. This will be done by using proven examples available in the literature from reliable experts: e.g., MIT Prof. Walter Lewin's physics examples,[11] many of which we have already used in previous courses, plus our own project-related, ME-based demo's such as gear trains and planetary gears. Lectures will be organized around a course-long "Lecture Case Study Project" that is designed to closely parallel the assigned design project so that ideas, concepts, and applications can be discussed in class in a relevant environment. For example, for the "egg-zooka" project we have used an imaginary "Flying Elephant" case study in which we propose that a circus has approached a company to expand the "man shot from a cannon" act to involve propelling an elephant to the top of the "big top" where it will snag a bag of peanuts hanging from a string. The goals are to size the springs needed for the act and determine the project's feasibility. This presents the opportunity to explain and demonstrate the concepts in this course, including: all of the design methodology steps[8] from determining objectives to setting design specifications; Newton's laws; a 1-D analysis of the finite difference of the elephant's flight, which the students must expand to 2-D in their design projects; and the ethics of animal experimentation.

Communication lectures include an introduction to the Three Laws of Professional Communication,[12] a standardized format for memos that we have begun using across the ME curriculum, specific guidelines and templates for the written and oral design project assignments, and an in-class exercise on team working agreements and decision making using the USAF airplane crash example.[10]

Laboratories. The laboratories involve seven lessons and assignments using the software required for making the CAD drawings required for this course (SolidWorks®) and the software for modeling particle motion in Working Model®. The remaining seven laboratories are used to teach specific skills the students need for their projects (shop safety and the use of simple hand tools—e.g., drill speeds and feeds for various materials), and to have the students perform the construction, assembly and testing needed for the design projects. Specifically the students will learn how to: a) wind, heat-treat and characterize springs to get their spring constants (by hanging water-filled bottles and measuring the resultant spring deflection); b) solder the electronic components into their UMEBs and program those boards for experiments involving measuring the LVDT displacement and activating/deactivating the solenoid; and c) calibrate the solenoid and LVDT. Each assignment will be designed so that if the students come prepared they can complete the laboratory assignment during the three-hour laboratory meeting.

Homework Assignments. Weekly homework assignments will be given for learning how to use spreadsheets. Specific homework assignments will be developed that will be oriented around the case study project. It is our experience that much of early spreadsheet material can be learned from the text with a minimum number of associated lectures. For more complex materials, lecture and laboratory instruction are provided.

In all classes we will develop and utilize a modular approach so that these courses remain economical and easy to implement for us and other institutions. For example, in our current ME 1000 course we have had enrollments of up to 160, with the course taught by one instructor, plus four lab TAs (two labs of 20 students each for each TA), a grader, and the two communication instructors. This model works well with the students receiving close to individualized instruction in their three-hour laboratory sessions (primarily SolidWorks® and Working Model® in our current ME 1000 course).

4.2 Semester 2: Introduction to the Design of Robotic Systems II (ME 1010)

The unifying emphasis of the second course is the use of MATLAB® and the extension of kinematics, dynamics and elasticity to rotational systems as detailed in Table 5.

Table 5. ME 1010 Lecture and Laboratory Modules.

Lectures	Modules
8	**Primary theme:** Model-based design, MATLAB® programming
6	**Engineering science theme:** rotational motion (velocity, acceleration, torque, moments, moment of inertia, torsion)
2	**Design/professionalism emphasis:** Ethics
1	**Communications theme:** Teamwork and decision making
2	**Numerical methods**: Roots of equations, statistics, numerical integration
4	**Mechanical hardware:** DC motors, gears, gear trains, fourbar linkages
2	**Electrical hardware:** Transistors, diodes, A/D, PWM
1	**Sensors:** Accelerometers, optical encoders, tachometers
1	**Manufacturing:** Microfabrication
1	**Other:** Design methodology

Labs	Modules
2	**Engineering software:** SolidWorks® (advanced)
4	**Engineering software:** Working Model®
1	**Mechanical hardware:** Gears (characterize)
1	**Electrical hardware:** DC motor (characterize)
1	**Electrical hardware:** UMEB (assemble and test, part 2)
1	**Sensors:** MEMS accelerometer (fabricate and characterize)
4	**Manufacturing:** Lathe, milling machine (introduction)

4.3 Semester 3: Introduction to the Design of Sustainable Energy Systems I (ME 2500)

The unifying engineering science theme of the third course is fluid dynamics. The modules that will be developed for this course are detailed in Table 6.

Table 6. ME 2500 Lecture and Laboratory Modules.

Lectures	Modules
8	**Primary theme:** Model-based design, C++ programming
4	**Engineering science theme:** Fluid dynamics (coefficient of drag, friction factor, Bernoulli's equation)
2	**Design/professionalism emphasis:** Economics
1	**Communications theme:** Conflict resolution
2	**Numerical methods**: Simultaneous linear equations, ODEs, implicit finite difference
5	**Mechanical hardware:** Servo motors, pneumatics, hydraulic actuators, planetary gears, chains, belts
4	**Electrical hardware:** Op-amps, filters
1	**Sensors:** Pressure sensors, flow meters
1	**Other:** Design methodology

Labs	Modules
5	**Engineering software:** LabVIEW®
2	**Electrical hardware:** Op-amp circuits (build and analyze using LabVIEW®)
1	**Electrical hardware:** UMEB (assemble and test, part 3)
1	**Sensors:** Pressure and flow sensors (characterize)
5	**Manufacturing:** Lathe, milling machine (advanced), NC router

4.4 Semester 4: Introduction to the Design of Sustainable Energy Systems II (ME 2510)

The unifying engineering science theme of the fourth course is thermodynamics and heat transfer. The modules that will be developed for this course are detailed in Table 7.

Table 7. ME 2510 Lecture and Laboratory Modules.

Lectures	Modules
8	**Primary theme:** Model-based design, numerical methods (non-linear eqns., PDEs, experimental design), TK Solver®, EES®
4	**Engineering science theme:** Thermodynamics and heat transfer (conservation of energy, heat transfer modes)
2	**Design/professionalism emphasis:** Project management
2	**Communications theme:** Technical leadership
6	**Mechanical hardware:** Stepper motors, AC motors, worm gears, power screws
3	**Electrical hardware:** AC power, data collection, Peltier device
1	**Sensors:** Thermocouples, thermistors, infrared sensors
1	**Manufacturing:** CNC methods
1	**Other:** Design methodology

Labs	Modules
1	**Engineering software:** LabVIEW® (advanced)
2	**Engineering software:** COMSOL®
5	**Engineering software:** COSMOS®
2	**Mechanical hardware:** Stepper motor, AC motor, Peltier device (characterize)
1	**Electrical hardware:** UMEB (assemble and test, part 4)
1	**Sensors:** Temperature sensors (calibrate)
2	**Manufacturing:** NC mill, vacuum former, injection molder

Finally, these courses will be constructed so they build in a coordinated manner both among themselves and with other required courses. For example, the students' design methodology skills will be built upon and extended each semester through the careful selection of the ongoing, integrated design projects, as will the students' computational, CAD and programming skills and the secondary physics themes.

5. Implementation

At the time of this writing we have implemented this approach in a single course (ME 1000) in the fall semester 2009, and begun teaching the second course (ME 1010) in the two-course first-year sequence. Three companion papers give descriptions of our initial experiences with: active learning tools,[13] the integration and spiraling of concepts and tools,[14] and engineering communication skills.[15] Those papers also indicate some of the modifications and changes we have already made based on our initial experiences. In terms of the general results we have found that:

- The use of student response systems ("clickers") is well accepted by the students and has significantly improved attendance and in-class student participation.
- We have begun a successful introduction to SolidWorks® that can be distributed over the four-semester sequence, thus continually reinforcing the students' learning of an important CAE skill.
- We have introduced a new, acronym-based approach to teaching design methodology, which we hope will help the students become both more creative and more systematic in their approach to design problems. That is, the ABCDEs of design, where:

    A = Assess: Assess the problem and stakeholders; have a good problem definition;

    B = Brainstorm: Spend time thinking about alternative ideas;

    C = Compute and Construct: Iterate computationally as much as you can and construct critical prototypes as needed;

    D = Decide: Make your design decisions in a transparent, organized and systematic way;

    E = Evopterate: Remember that designs **Evo**lve and are **opt**imized as designers i**terate** through successive attempts; and

    S = "Satisfice:"[16] Remember that in general final designs will not be perfect but will involve compromises, and will become close to optimal by *satisfying* some goals while *sacrificing* others.

We are encouraged by our first semester's efforts, and will continue to make modifications to these courses while keeping our underlying theme, so that we can continue to improve our future engineers' education.[17]

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