AC 2010-1837: INTEGRATION AND REINFORCEMENT OF MECHANICAL ENGINEERING SKILLS BEGINNING IN THE FIRST-YEAR DESIGN EXPERIENCE

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Integration and Reinforcement of Engineering Skills Beginning in the First-Year Design Experience

Abstract

As the first step in implementing a Student-driven Pedagogy of Integrated, Reinforced, Active Learning (SPIRAL) throughout our Mechanical Engineering curriculum, we are modifying two freshman courses to *introduce*, *integrate* and *sequentially reinforce* multiple engineering topics that lay a foundation for subsequent, more focused ME coursework. Our approach builds on Bruner's[1] concept of a "'spiral curriculum' that turns back on itself at higher levels" through repetition at ever-increasing depths of knowledge. By integrating topics throughout the curriculum that are typically only taught in separate, disconnected engineering classes, and doing so in a design-oriented context, students are forced to repeatedly "parallel process" various engineering skills much as they will be expected to do in engineering practice. Integration also facilitates a redistribution of engineering topics throughout the entire curriculum that (1) reinforces student understanding and retention through reinforcement at short intervals, and (2) minimizes fading of conceptual knowledge due to extended disuse – as is often problematic in the traditional ME curriculum.

Introduction

Historically, engineering education has followed a linear model in which engineering topics are taught in separate, disconnected classes that "serially encapsulate" the course material in the students' minds. In contrast, our newly developed first-year course sequence, funded by a Course Curriculum and Laboratory Improvement Phase 1 Grant from the National Science Foundation titled "Design-Based SPIRAL Learning Curriculum" (DUE-0837759), strives to integrate a variety of engineering topics in an effort to introduce students to (1) important science and math concepts in an engineering context, and (2) the complexity and multifaceted nature of professional engineering practice. Research studies suggest that such an integrated approach can transform engineering education's historical goal, i.e., the acquisition of engineering science/math knowledge, to also include the goal of professional development.[2] Engineering programs that integrate science, math, and engineering topics have been shown to produce students that are more likely to pass core engineering courses, more self-confident in their engineering abilities (including communication), and more likely to stay in an engineering program and make progress towards a degree.[2] In addition to these benefits, we anticipate that the integration of design, professionalism, engineering science principles and computational tools and skills will prepare students to be much better practicing engineers. Moreover, the repetition of basic concepts throughout the curriculum is expected to enhance students' mastery of engineering science/math principles and their appropriate implementation. This paper will address the ways in which we have implemented (1) the *introduction* and (2) *integration* of engineering science concepts and engineering practice skills, and (3) the *reinforcement* of those topics in our newly developed freshman design experience in preparation for further integration and reinforcement in later courses.

Overview of Integrated First-Year Courses

In our new SPIRAL curriculum, first-year students take ME 1000 and ME 1010, a two-course sequence titled “Introduction to Robotic Systems Design I/II.” These courses replace a stand-alone freshman design course titled “Engineering Design and Visualization” that introduced students to various aspects of Mechanical Engineering, and a separate Computer Science programming course. In order to implement the integrating theme of Robotics/Mechatronics (a theme chosen to introduce and integrate the teaching of kinematics and dynamics, mechanisms, sensors and actuators), the new ME 1000 course focuses on the mechanical aspects of robotic systems, while the new ME 1010 reinforces, applies and expands on those mechanical aspects, and also introduces sensors, actuators and computer control of integrated mechatronic systems, again in the context of robotics. The integrated engineering topics introduced in ME 1000 include: design methodology, mechanical hardware, manufacturing tools, spreadsheets, 3D CAD, Newton’s laws for linear and rotational motion, graphing and numerical techniques, statistical analysis, oral and written communication, teamwork, and safety. ME 1010 builds on these topics and additionally introduces computer programming, electricity and magnetism, electronic circuits, economics, and ethics. These topics are introduced and reinforced in the various course components: lectures, labs, reading assignments, problem sets, a team design project, and communication assignments.

In such multifaceted courses, the successful integration of topics and interconnection of course components poses a significant challenge, especially considering the diverse experience and knowledge levels of our students in these introductory courses with minimal pre-requisites. The overarching “robotic systems” theme has played a key role in addressing this integration challenge. For example, in ME 1000 we have formulated a series of robot-themed problems to teach both Excel® and SolidWorks®; this connection to the course theme motivates learning of otherwise isolated, and possibly mundane, skills. The team design project – involving the design, construction, and competition of a set of cooperative mechanical robots (to play “robot volleyball” in the first course offering) – is structured to draw upon concepts learned and skills acquired in lectures, labs and problem sets. The communication and teamwork instruction and assignments are also tied to the design project so as to make them relevant, not merely required. Additionally, the multi-component nature of ME 1000 provides an easy way to reinforce learning during the semester. For example, fourbar linkages are (1) introduced in lecture, (2) analyzed in Excel® assignments, (3) demonstrated using hands-on kits, (4) animated in SolidWorks®, and (5) designed and manufactured during the semester, to be used in each student’s competition robot.

Integration of Course Components

The first integration challenge in our new classes is tying together the multiple course components: lecture, laboratory, reading assignments, problem sets, communication assignments, and design project. Specifically, in the old ME 1000 course, Excel® assignments and SolidWorks® labs were stand-alone components with minimal relation to topics discussed in lecture. In the following examples, we will discuss strategies used to make the ME 1000 laboratories and problem sets more integral to the main body of the course.

Example 1: Laboratories

In the new ME 1000 course, the focus of most (9 of 13) of the laboratories remained 3D CAD using SolidWorks®. This base was then augmented with several hands-on labs related to mechanical hardware topics that were discussed in lectures and utilized in the team design project. For example, following a lecture on fourbars that included several practical examples and in-class demonstrations, a lab assignment taught students to perform dimensional synthesis of fourbars using graphical techniques. The students modeled the synthesized fourbars in SolidWorks®, and these models were then used to introduce the students to the animation capabilities of SolidWorks®. In a subsequent lab, students were provided with fourbar kits and instructed to assemble physical models of Class 1, 2 and 3 fourbars in order to explore the functionality and inversions of each (Figure 1a). Students were also provided with materials to make foam core prototypes of their fourbar designs for their “volleybots” (Figure 1b); each “bot” was required to utilize at least one fourbar. The students were required to bring SolidWorks® drawings of their fourbar designs to the prototyping lab. Finally, students were required to each manufacture a fourbar for their “volleybot” on the waterjet cutter from their SolidWorks® drawing, and use that design in the end-of-semester competition, as shown in Figure 2. (A video showing one team’s “volleybots” serving, bumping, setting, and spiking a squash ball can be viewed at http://www.youtube.com/watch?v=ZT_8tIFz41s.) As a result of these activities, the fourbar labs connected to both lecture content and the design competition, and also tied hands-on learning (graphical synthesis, physical models, and prototypes) to SolidWorks® exercises (modeling, animation, and 2D drawings). Other new hands-on labs included a spring lab and a gear lab.[3]

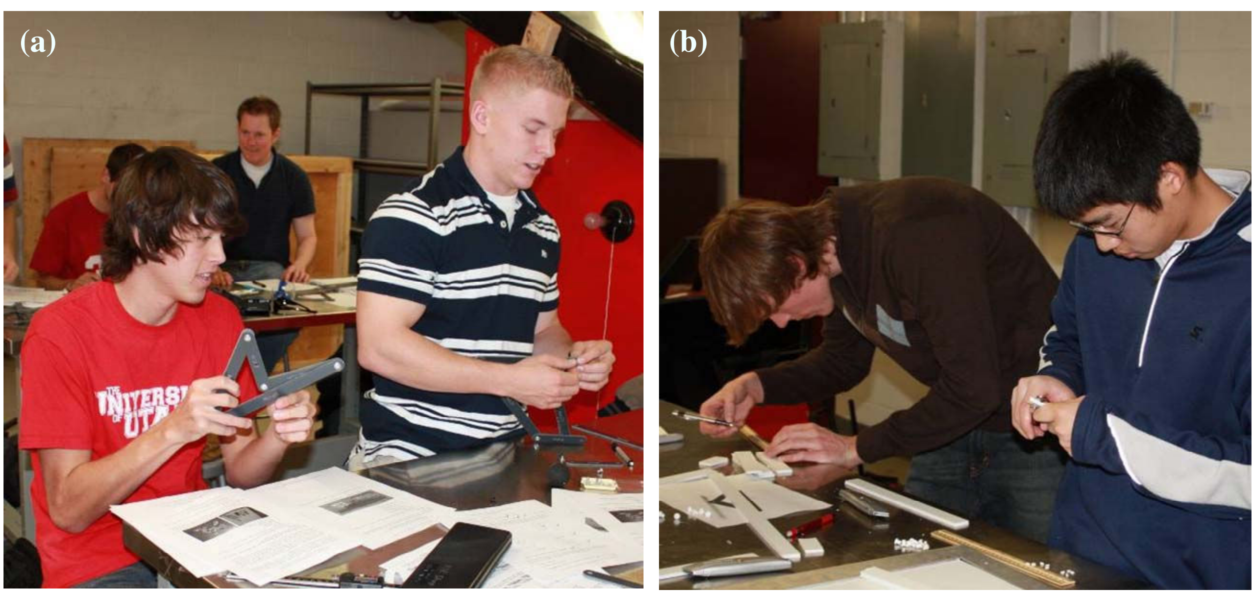

Figure 1. (a) ME 1000 students analyzing fourbar functionality using fourbar kits (machined on a waterjet cutter by course TAs). (b) ME 1000 students making critical function prototypes of their “volleybot” fourbar designs.

Figure 2. (a) ME 1000 students manufacturing fourbars on the waterjet cutter in the ME machine shop. (b) The students' CAD drawing on the waterjet computer. (c) The waterjet nozzle above several cut fourbars. (d) A set of "volleybots" with fourbars.

In addition to implementing new hands-on laboratory exercises related to lecture content and the design project, we also made an effort to weave the overarching robotics theme into the SolidWorks® exercises by having the students model robot parts instead of the arbitrary objects assigned in previous years. For example, on the SolidWorks® proficiency portion of the ME 1000 final exam, students were asked to model and assemble three parts making up the simplified robot "R1D1" shown in Figure 3a. In future offerings of ME 1000, we plan to make use of parts from "MECH•E" (Figure 3b,c), a robot designed by a 2008-09 senior design team to demonstrate the Arduino® Duemilanove augmented microcontroller to be used by students in ME 1010 and follow-on courses.

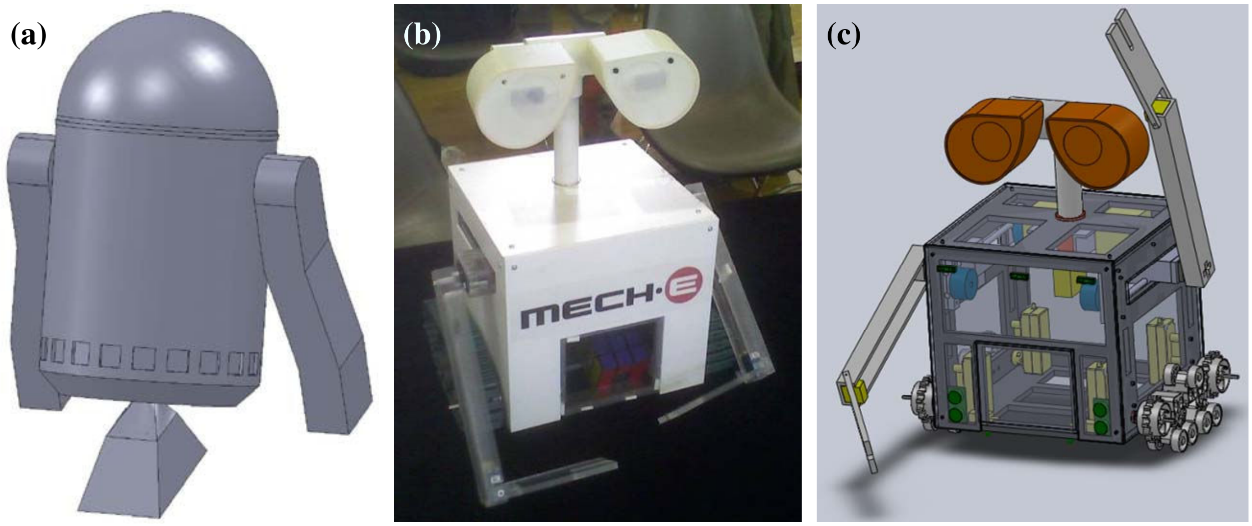

Figure 3. (a) SolidWorks® model of “R1D1” assigned on the final competency exam. (b,c) “MECH•E” robot whose parts will be incorporated into next fall’s ME 1000 SolidWorks® labs.

Example 2: Problem Sets

The goal of the ME 1000 problem sets is to teach students spreadsheet skills along with numerical methods (such as explicit finite differences and least squares line fitting) and physics concepts. In the old ME 1000, this was accomplished by having the students read an Excel® textbook and solve the provided problems. As such, the problem sets were a stand-alone course component, with only partial connections to lecture topics. For the new ME 1000, we developed original Excel® problems, which allowed us to (1) tie the Excel® assignments to the course content through robotics-themed problems and (2) reinforce engineering topics covered in lectures by including relevant engineering physics and mechanical hardware problems, all while teaching the same basic spreadsheet skills. Of 28 total problems assigned throughout the semester, 17 were robotics-themed; of the remaining 11, six were related to mechanical hardware discussed in lectures (fourbars, springs, gears). Ten of the 28 problems were related to engineering physics concepts discussed in lecture.

The following are examples of robotics-themed problems used to teach basic spreadsheet skills. “Data” from a PUMA® (Programmable Universal Machine for Assembly) robot were used to teach students how to plot bar graphs and pie charts. Velocity “data” from a Roomba® Vacuum Cleaner Robot provided the context for learning to plot histograms. Mars Rover “data” was used to set up a problem that reinforced Newton’s laws while teaching students how to use the least squares fit procedure for non-linear functions. The goals for these and other robotics-themed problems were to increase student interest, connect the problem sets to course content, and repeatedly reinforce the physics and robotic/mechatronic concepts discussed in lecture.

The design project was an additional means of integrating the computational and engineering science concepts presented in the problem sets. One of the design project assignments required the use of the Explicit Finite Difference (EFD) technique to predict the trajectory of a thrown ball, with EFD calculations performed in Excel®. In preparation for applying the EFD technique to their device designs, the students worked three EFD homework problems (one simple example, and two more complex problems involving springs that were also very relevant to the design project) in Excel®. One of the goals of the design project EFD predictions was to demonstrate the power of computational tools (spreadsheets in this case) and motivate students to put in the time necessary to become proficient using such tools.

Integration of Engineering Topics

In addition to integrating course components (lecture, laboratory, reading assignments, problem sets, communication assignments, and design project), it is also necessary to integrate course topics – i.e., design methodology, communication skills, engineering science, engineering hardware, CAD and manufacturing skills, engineering computation and numerical techniques, and professional engineering skills – so that they effectively complement each other to enhance the learning experience, and do not seem disjointed to the students. As a first approach, we have tried to address each topic in multiple course components, as detailed in Tables 1-7. For example, Table 1 shows that the various *design methodology* tools were both addressed in lecture and utilized in the team design project, while Table 3 illustrates that the ME 1000 *engineering physics* topics (Newton's laws, linear motion, rotational motion) were covered in lecture and in-class demos, reinforced in multiple problem sets, and required for modeling aspects of the design project. Tables 1-7 will be discussed in more detail in the following section with regards to reinforcement of engineering topics via the SPIRAL approach of the new courses.

The design project is by far the most effective means of tying together all of the engineering topics within ME 1000 and ME 1010. Design project assignments in ME 1000 require students to utilize various *design methodology* tools such as Objectives Trees in the assessment phase, Morphological Forced Connection Charts in the brainstorming phase, and Decision Matrices in the decision-making phase. The *engineering physics* topics prepare the students to predict the performance of their devices in the computation phase, and calculations are made using *engineering computational tools* (Excel® in ME 1000 and MATLAB® in ME 1010) and *numerical techniques* (e.g., the Explicit Finite Difference technique for numerical integration introduced in ME 1000). The devices require the use of certain *engineering hardware*, e.g., fourbars and springs in ME 1000, and motors, actuators and sensors in ME 1010, each of which are discussed in lecture and demonstrated in laboratories. Students use their *CAD* skills to model their designs, and then *manufacture* their designs using handtools, the waterjet cutter (in ME 1000), and rapid prototyping (in ME 1010). *Communication* is also an integral part of the design project. In ME 1000, each design project assignment involves either a written engineering memo or a team oral presentation, and in ME 1010 the students also write a final report on their design. Communication learning is aided by team consultations with the communications instructors from our college-wide CLEAR (Communication, Leadership, Education And Research) Program; throughout ME 1000/1010, these consultations focus on writing, oral presentations, and teamwork. Since the design project is team-based, *teamworking skills* are also emphasized in lectures, including in-class team activities, and in the design project assignments.[4] At the beginning of each semester, each team formulates a working agreement in consultation with the teamwork instructor, and at the end of the semester each team prepares a memo critiquing their teamwork efforts. In addition, the design competition provides a venue for instruction in *professional skills* such as safety, economic considerations in design and manufacturing, and engineering ethics.

Reinforcement of Engineering Topics

Reinforcement of key concepts is also a primary goal of the restructuring of our curriculum. We have implemented reinforcement at many levels – within a single course, within this two-course first-year sequence, within a second, sophomore-level sequence, and throughout the four-year curriculum – as illustrated by the examples below. At the most basic level we reinforce the concepts presented in lectures and reading assignments by using automated student response systems (i.e., "clickers") to administer quizzes at the start of each lecture.[3] At the end of each quiz, we review the questions and highlight key points, spending extra time on questions with which the students had difficulty. Other means of reinforcement include addressing topics in multiple course components within a course, returning to topics in a subsequent course and addressing or applying them at a higher level, and building on certain skills – e.g., the application of design methodology, communication and teamwork skills – throughout the entire engineering curriculum.[5] For each such subject, as the students progress through our curriculum we reinforce previous concepts and skills and introduce new ones. For example, instead of having a single introductory class wherein the students learn SolidWorks®, in the new first- and second-year course sequences the students will acquire SolidWorks® skills through lessons, assignments and projects during each of four sequential semesters in their first two years. They will then be required to apply those skills in their junior-level Mechatronics design project and their capstone senior-level design project.

Example 1: Engineering Hardware – Reinforcement within Course

Table 4 illustrates how engineering hardware subtopics are reinforced within a single course by revisiting them in multiple components of the course. In ME 1000, for example, fourbars were introduced first in lecture, with definitions of classes and inversions complemented with videos and physical demos. Next, in lab the students learned how to perform graphical synthesis of fourbars, and then modeled and animated the fourbars in SolidWorks®. In a subsequent lab, the students used physical fourbar models to experiment with the functionality of the different fourbar classes and inversions. In addition, the design project required the use of fourbars, which the students designed and modeled in SolidWorks®. The students assembled critical function prototypes of their fourbar designs as part of a lab exercise, and then manufactured fourbars on a waterjet cutter for their competition robots. Lastly, two of 28 Excel® problems were related to fourbars: one in which the students analyzed S + L ? P + Q to determine the Grashof condition, and one that applied Excel®'s Solver function to solve for the output angle if the input angle and link lengths are known.

In the old ME 1000, students saw fourbars in one lecture (including synthesis examples), were required to use fourbars in the design project, and performed the S + L ? P + Q in Excel®; new this year were the hands-on laboratory experiences of synthesis, physical models, and prototyping; animation of fourbars in SolidWorks®; and an additional Excel® problem. As a result of these additions, the performance on identical fourbar questions on the final exam improved from 53.1% in Fall 2008 (old ME 1000) to 86.5% in Fall 2009 (first offering of the new ME 1000). This and other preliminary assessment data related to active learning strategies in our new courses is provided in more detail in a companion paper.[3]

Springs were also discussed in lecture, explored in labs and in problem sets, and utilized in the design project. In the “spring lab,” students measured displacement as a function of water volume for helical compression and extension springs, and a rubber band (Figure 4a). In a subsequent Excel® assignment, the students entered their data and calculated spring constants. The spring constants were then uploaded via the web and used to illustrate statistical distributions in lecture. Because the focus of ME 1000 was mechanical systems, the design project devices could utilize mechanical power only; hence, most students utilized springs in their devices (Figure 4b). Engineering science lectures on Newton’s laws and linear motion used the “egg-zooka” – an extension spring-powered egg shooter – as a demo, and the motion of the egg was analyzed in class using the EFD technique. The students were then given two challenging, circus-themed homework problems in which the EFD technique was applied to (1) a compression spring used to shoot an elephant (linear motion) to the top of a circus tent and (2) a torsion spring used to shoot a tiger (projectile motion) through a flaming hoop.

Figure 4. (a) ME 1000 students performing displacement vs. force measurements on springs. (b) A “volleybot” utilizing a spring for its mechanical power source.

Example 2: SolidWorks® – Reinforcement within the ME 1000/1010 Sequence

In our old ME curriculum, SolidWorks® was taught as part of ME 1000, and then our students did not use SolidWorks® again until the two-course Mechatronics sequence in the junior year, by which time their SolidWorks® proficiency was significantly reduced. The addition of ME 1010 to the curriculum offers the possibility of reinforcing and building on students’ ME 1000 SolidWorks® skills. In three new SolidWorks® labs, we first review the tools learned in ME 1000 with an emphasis on the analysis of a part to determine the most efficient way to model it using SolidWorks®. The second SolidWorks® lab has students model gears (which also reinforces this mechanical hardware topic that was introduced in ME 1000 and is utilized in the ME 1010 design project), while the third lab introduces students to the SolidWorks® Motion feature (while also teaching students about various mechanisms, e.g., fourbars, Geneva, quick-return). Moreover, the design project itself will require the use of SolidWorks® to model device parts and assemblies. With similar new integrated second-year courses set to come online in the next academic year,[5] the students will gain even more exposure to the capabilities of

SolidWorks®, both in laboratories and through design projects, where we will utilize additional tools such as stress, flow and thermal calculations. We anticipate that these activities will both increase our students' overall SolidWorks® competency and eliminate the current struggle to regain competency when required in Mechatronics and Senior Design.

Example 3: Engineering Math and Physics – Reinforcement in Conjunction with Required Math and Physics Courses

Calculus is not a pre-requisite for ME 1000 (but is a co-requisite), so many of our students are in Calculus I while they are taking ME 1000. Likewise, since Calculus I is a pre-requisite of Physics I, many of our students do not take Physics I (Mechanics) until the spring semester, i.e., concurrent with ME 1010. As such, we planned our kinematics lectures to come after students learned derivatives in Calculus I so that we could reinforce the engineering importance of derivatives in terms of instantaneous velocity and acceleration. Likewise, later in the semester when we introduced the Explicit Finite Difference technique, students were simultaneously being introduced to integration in Calculus I. Numerical integration via EFD to obtain velocity from acceleration and position from velocity was intended to not only reinforce integral calculus concepts but also make students aware that many engineering problems do not have closed-form solutions and must be solved numerically. With regards to engineering physics, in ME 1000/1010 we present physics topics that many students will not see in a Physics course until the following semester. We "deal" with this by keeping the physics instruction simple, and use our courses as an opportunity to excite the students about what they will learn in subsequent semesters. By providing a mechanical engineering context for math and physics learning early on, we hope to motivate the students to apply themselves in their core math and science courses, where the basic concepts we have introduced will be reinforced and taught in greater depth.

Example 4: Design Methodology – Reinforcement throughout the Four-Year Curriculum

Design methodology has always been a primary focus of ME 1000. In the old curriculum, students left ME 1000 to take sequential engineering science courses, and did not see another design course until Mechatronics in the junior year. In our new curriculum, students will be in a design project-based course every semester of their four-year engineering education, as ME 1000/1010 will be followed by the new second-year course sequence ME 2500/2510, "Introduction to the Design of Sustainable Energy Systems I/II." ME 2500 will be an integrated class replacing the traditional Numerical Methods course, while the focus of ME 2510 will be thermodynamics (replacing a stand-alone traditional Thermo I course). Both of these classes will have design projects; in 2500 related to wind or water power, and in 2510 related to solar or other alternative energy methods used to generate power. ME 3200/3210 Mechatronics is currently a design project-based course in the junior year, and is followed by ME 4000/4010 Senior Design in the senior year. These sequential design experiences are expected to better prepare our students for engineering practice by emphasizing creativity, teamwork, communication, and other professional skills.[2] The four-year sequence of design classes will allow us to truly spiral our design methodology instruction. In ME 1000, students are introduced to very basic design methodology tools. In ME 1010 and the subsequent design courses, these tools will be expanded on and new tools will be introduced, such that our students are constantly reaching a higher level of competency in engineering design.

Summary

In summary, by complementing serial (course-by-course) exposure to essential engineering topics and skills with a parallel (integrated) approach – presented in a design context – and by emphasizing reinforcement at progressive depth, *starting in ME 1000* and continuing through the four-year ME curriculum, we expect to see a significant improvement in our students' preparedness for their subsequent core engineering courses, and to improve their retention, understanding and ability to apply fundamental engineering principles and thus become more successful practicing engineers.

While we have utilized Mechanical Engineering themes, other engineering disciplines that currently have a discipline-oriented introductory course and a computer programming course could easily implement our SPIRAL approach in the first-year curriculum by reorganizing those existing courses into a sequence such as ours, with the robotics/mechatronics integrating theme and the engineering science topics replaced by a theme and topics more appropriate to that discipline.

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Table 1. Design Methodology

	ME 1000						ME 1010					
Subject	**Lectures**	**Demos/ Activities**	**Readings**	**Labs**	**HWs**	**Design Project**	**Lectures**	**Demos/ Activities**	**Readings**	**Labs**	**HWs**	**Design Project**
Assessment	2		14			Required			5			Required
Brainstorming	1	1(A)				Required						Required
Computation	1					Required						Required
Construction	1					Required						Required
Decision Making	1	1(A)				Required						Required
Optimization and Iteration	1					Required						Required
3D CAD (see Table 6)												
Hand Drawing				2		Required				2		Required

Table 2. Communication Skills

	ME 1000						ME 1010					
Subject	**Lectures**	**Demos/ Activities**	**Readings**	**Labs**	**HWs**	**Design Project**	**Lectures**	**Demos/ Activities**	**Readings**	**Labs**	**HWs**	**Design Project**
Teamwork	2	2(A)	2			Required	1	1(A)	2			Required
Oral Presentations	1					Required	1					Required
Writing	1	1(A)				Required	1	2(A)				Required

Table 3. Engineering Science

	ME 1000						ME 1010					
Subject	**Lectures**	**Demos/ Activities**	**Readings**	**Labs**	**HWs**	**Design Project**	**Lectures**	**Demos/ Activities**	**Readings**	**Labs**	**HWs**	**Design Project**
Newton's Laws	2			1	4	Required						Required
Linear Motion	2	1(D)	4		7	Required						Required
Rotational Motion	1	1(D)			1	Used by some students						Required
Electricity & Magnetism							1	1(D)	1			Required
Circuits/Computer Control							1		1	2		Required

Table 4. Engineering Hardware

	ME 1000						ME 1010					
Subject	**Lectures**	**Demos/ Activities**	**Readings**	**Labs**	**HWs**	**Design Project**	**Lectures**	**Demos/ Activities**	**Readings**	**Labs**	**HWs**	**Design Project**
Springs	1	1(D)		1	3	Utilized						
Fourbars	1	1(D)		2	2	Required						Required
Gears	1	1(D)		1	1							Required
DC Motors							2	1(A)	1	1		Required
Solenoids							1	1(A)	1	1		Required
Circuit Elements							2		1	1		Required
Sensors							2	1(A)	1	1		Required

Table 5. CAD and Manufacturing Skills

	ME 1000						ME 1010					
Subject	**Lectures**	**Demos/ Activities**	**Readings**	**Labs**	**HWs**	**Design Project**	**Lectures**	**Demos/ Activities**	**Readings**	**Labs**	**HWs**	**Design Project**
SolidWorks®				9		Required						Required
Shop Safety	1			1		Emphasized						Emphasized
Hand Tools				1		Utilized						Utilized
Waterjet Cutter	1			1		Required						Available
Metrology	1		1							2		
Rapid Prototyping							1			1		Required

Table 6. Engineering Computation and Numerical Techniques

	ME 1000						ME 1010					
Subject	**Lectures**	**Demos/ Activities**	**Readings**	**Labs**	**HWs**	**Design Project**	**Lectures**	**Demos/ Activities**	**Readings**	**Labs**	**HWs**	**Design Project**
Excel®			2		10	Required				2		Available
MATLAB®							13		13		6	Required
Explicit Finite Difference	2		1		4	Required						
Least Squares	1				2							
Statistics	1		1		1							

Table 7. Professional Engineering Skills

	ME 1000						ME 1010					
Subject	**Lectures**	**Demos/ Activities**	**Readings**	**Labs**	**HWs**	**Design Project**	**Lectures**	**Demos/ Activities**	**Readings**	**Labs**	**HWs**	**Design Project**
Communication (see Table 1)												
Safety	1			1			1	1(A)	1			Required
Economics							1	1(A)	1			Required
Ethics							1	1(A)	1			

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