AC 2008-2230: A PRACTICE-INTEGRATED UNDERGRADUATE CURRICULUM IN MECHANICAL ENGINEERING

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A Practice-Integrated Undergraduate Curriculum in Mechanical Engineering

Abstract

Project-based and experiential learning is becoming increasingly important in engineering education. When recently surveyed, a majority of the students in a junior-year class at the University of Pennsylvania stated that they learned more from a particular course that had a strong lab component than from any other college class. This student belief may stem from the internal confirmation of understanding that hands-on work provides. Students seem to gain confidence when they are able to apply class material successfully to real-world systems, rather solving text book problems on paper. It is not yet clear where the critical learning takes place, whether in the lab or in the associated lecture, but it is obvious from our experience that laboratory work catalyzes student understanding and excitement about mechanical engineering.

Based on student feedback and our belief in the value of project-based and experiential learning, we have developed a practice-integrated mechanical engineering curriculum that spans the full four-year undergraduate experience. Our goal is to ingrain theoretical concepts and develop independent student thinking by gradually incorporating design into laboratory activities; by exposing students to systems and applications before developing all of the relevant theoretical concepts; and by motivating students to appreciate the importance and relevance of the theory by directly applying it in projects.

This curriculum incorporates three principal educational strategies. First, our laboratory classes provide a steady progression of skills and independence, from freshman through junior year. Second, many concepts are taught in a top-down framework, which exposes students to relevant physical systems and practical applications before they have been taught the specific theoretical concepts. Third, lecture material is formulated to support the laboratory activities, in contrast to the traditional approach where laboratory exercises are decoupled from or tangential to the lectures.

In this paper, we describe the specifics of our practice-integrated curriculum, using examples from basic engineering science classes that have been redesigned to try to provide a more meaningful learning experience for our students. A steady increase in enrollment numbers and positive feedback from student evaluations demonstrate the benefits of this curriculum.

Introduction

Laboratory and project-oriented teaching[1] is becoming more prevalent in engineering. Project-oriented instruction can ingrain theoretical concepts by challenging students to apply theory in design settings where they must think for themselves. We believe that it is projects that students relate to and indeed depend on in order to understand the importance of what they are taught.

Although basic science, mathematics, and the other principles taught at the early undergraduate level have not undergone significant changes, the applications of these fundamentals are changing quickly. Viewed broadly as paradigm shifts in technology, the pace of these changes is increasing exponentially[2]. One clear consequence of this pace of technology is that the content in a curriculum needs to change more often to stay up to date and relevant. Tapscott espouses that in the context of a digital economy, some of the content of technical undergraduate degrees is obsolete even by the time students graduate[3]. Regarding the use of labs, it is not so much that the concepts taught are obsolete as they are no longer relevant to current technology.

Another consequence of the rapid pace of technology is that to be effective, teachers must also update their methods. This realization comes from the belief that technology changes people and their culture. Today's students are raised on different technology than the people who teach them. Brown and Hagel describe this effect as "push vs. pull" in the information age[4]. While most professors grew up watching TV (where information was "pushed" to them), today's undergraduates are accustomed to interactive games and the Internet. They are accustomed to choosing what they want to see, and they "pull" whatever content they desire. Teachers can be more effective for a broader set of students by employing a modality with which students are already very familiar.

In addition to the rapid pace of technological change, engineering is also becoming increasingly interdisciplinary. While exercises and problem sets work well to test a student's grasp of individual ideas, we believe that the integration and application of multiple concepts is best applied in larger project or lab settings. Traditionally, undergraduate curricula in mechanical engineering include a capstone design project that occurs during the senior year. Students in engineering at the University of Pennsylvania and other universities typically parts of two or three courses learning how to deal with integration, the practical aspects of teamwork, interacting with project sponsors from business or research, and how to apply theoretical concepts to real engineering problems often in the context of a senior design project. We believe that this approach is too little too late.

Of course, it is not feasible to have a senior design project during the freshman year; first year students don't yet have the knowledge or skills that are required to succeed at such an endeavor. However, a progressive methodology can be incorporated early in a curriculum to enable students to build project-based experience and skills over their undergraduate education. At the same time, application-oriented projects can motivate student learning and imbue traditional concepts with modern relevance.

Recognizing these directions, we have developed a Practice Integrated Curriculum (PIC) that is

- Lab focused (project oriented)
- Evergreen (lab assignments change each year)
- Progressive (student independence and design content increase each year)

We recognize that these individual concepts are not new to the domain of engineering education. A variety of other universities around the world have also been exploring the merits of project-based learning[1, 5].For example a large portion of the curriculum at Olin college, a new engineering school in Massachusetts, is focused on project based teaching. They also rely on student input to help design and improve the curriculum every year. This paper describes the approach we have taken at the University of Pennsylvania, which integrates selected teaching techniques into a cohesive mechanical engineering curriculum aimed at facilitating our students' development into competent, motivated, independent engineers.

Progression

Full curriculum integration has several advantages over labs that are simply tied to individual courses. The most obvious benefit is the potential for projects to apply integrated concepts that cross many courses. At the same time, soft skills such as teamwork, instrumentation, fabrication, information retrieval, technical writing, and the scientific process can be taught progressively over four years. Skills build on each other from one year to the next, enabling students to develop independence and ultimately acquire a sense of engineering empowerment.

PIC follows a progression that is loosely metaphorical to human growth. Just as a human child ultimately learns the ability to survive in a world independent from his or her parents, we strive to enable students to learn concepts and applications to the point where they can apply them in an unstructured environment outside the classroom.

- **Freshman year.** Like toddlers learning new words, following simple instructions, and exploring the world, freshmen are raised from the infancy of high school through active engagement in structured activities. Laboratory work emphasizes the testing of established principles in mechanics and introduces connections to current engineering phenomena.

- **Sophomore year.** As early childhood learning is characterized by increasing freedom in exploration, the second year labs and projects start to introduce design in constrained spaces using pattern synthesis.

- **Junior year.** When children reach adolescence, the primary goal is to prepare them to be independent adults. The projects become open ended. Design challenges and experimental labs have less instruction and more presentation of the problem, leaving the solution space open for students to explore and solve.

- **Senior year.** At this point, students are expected to have the skills and knowledge to perform without constant supervision. The senior design project is their opportunity to utilize all of their abilities in one large endeavor from start to finish.

Brown and Hagel emphasize that with the access to a plethora of knowledge and resources, we need expand the choices for our students to find those most relevant and effective. To give them "the tools and resources (including connections to other people) required to take initiative and creatively address opportunities as they arise," we need to teach them to take ownership of their own learning not only because they can, but also because they will be expected to after they graduate[4].

Lab-oriented coursework

The field of mechanical engineering is so broad that the question is never what material to include in a course, but rather what material to leave out simply because there is not enough time to cover everything. In PIC, the labs and projects drive the curriculum. What this means is that the choice of theoretical materials (and the order in which they are covered) aligns with the choice of lab topics.

In order to stay relevant consistently, a significant portion of the projects need to change each year. Unfortunately, this puts increased burden on the teaching staff as content cannot be reused year to year. Another consequence of this turnover is that it is difficult to justify large investments in one-time setups (another traditional approach). This requires the teaching staff to be creative. We have found that some of the burden of lab and experimental setups can be put on the students as they gain independence, for example in designing their own experiments when given the basic tools and principles from which to work.

Top down framework

The top down framework is intended to integrate the lab experience both before and after detailed theory is presented. By exposing students to relevant physical systems and practical applications before they have been taught the specific theoretical concepts, students obtain a more intuitive grasp of the concepts and the motivation for relevance. As the students become more independent, the labs provide opportunities to apply the theory they learn in increasingly open-ended ways.

One of our motivations for the top down framework is the introduction of engineering concepts early in a student career. The early college years are usually composed mainly of math and natural science courses; thus, engineering students often question why they are involved in engineering (with the unfortunate effect that some students transfer to a different engineering major or abandon engineering altogether). We believe that introducing engineering during freshman year helps inspire students and thus retain them in engineering.

Practice–Integrated Curriculum

Overview

Following the dramatic changes in technology and the industrial base in the United States, we have seen curricula in mechanical engineering undergo a significant evolution over the last 20 years. We have met these changes by infusing design and hands-on laboratories throughout the undergraduate program, while simultaneously introducing new and popular courses such as robotics, mechatronics, and product design. Accommodating these updates required changes in our core Mechanical Engineering curriculum, such as consolidating two thermodynamics courses into one and combining statics and strength of materials into a single course. Increases in the design content of other core classes have also been met with a generally positive student endorsement.

			Freshman Year			
CU	**Fall**			**CU**	**Spring**	
1.5	**CHEM 101/053**	Intro to Chemistry & Lab		1	**MATH 114**	Calculus II
1	**MATH 104**	Calculus I		1.5	**PHYS 151**	Principles of Physics II & Lab
1.5	**MEAM 110/147**	Intro to Mechanics & Lab		1	Professional elective (e.g., Introduction to Computer-Aided Design)	
1	Social science or humanities (SSH) elective			1	Writing requirement (SSH)	
				1	Natural science elective	
			Sophomore Year			
CU	**Fall**			**CU**	**Spring**	
1	MEAM 105	Intro to Sci. Computing		1	**MEAM 203**	Thermodynamics I
1	**MEAM 210**	Statics & Strength of Matls.		1	**MEAM 211**	Eng Mechanics: Dynamics
.5	**MEAM 247a**	Mech Eng Laboratory I-A		.5	**MEAM 247b**	Mech Eng Laboratory I-B
1	**MATH 240**	Calculus III		1	**MATH 241**	Calculus IV
1	SSH elective			1	SSH elective	
1	Professional elective (e.g., Circuits & Syst.)					
			Junior Year			
CU	**Fall**			**CU**	**Spring**	
1	**MEAM 302**	Fluid Mechanics		1	**MEAM 333**	Heat and Mass Transfer
1	**MEAM 321**	Vibrations		1	**MEAM 348**	Mech Eng Design Lab
1	**MEAM 347**	Mech Eng Design Lab		1	**MEAM 354**	Mechanics of Solids
1	SSH elective			1	Math elective	
1	Free elective			1	MEAM Upper level course	
			Senior Year			
CU	**Fall**			**CU**	**Spring**	
1	**MEAM 445**	Mech Eng Design Projects		1	**MEAM 446**	Mech Eng Design Projects
1	MEAM Upper level (e.g., Mechatronics)			1	MEAM Upper level course (e.g., Energy Eng.)	
1	Professional elective (e.g., Aerodynamics)			1	Professional elective (e.g., Adv. Strength Mat.)	
1	SSH elective			1	SSH elective	
1	Free elective			1	Free elective	

Table 1: Sample 2007 University of Pennsylvania MEAM curriculum.

Table 1 shows the schedule of courses taken by a typical student in our department. Each lab course (MEAM 147, MEAM 247a/b, and MEAM 347/348) runs in parallel with one or more core lecture-style courses over the first three years. These lab courses are closely coupled with their concurrent MEAM course(s), introducing students to integrated engineering applications of the concepts they are learning in lecture and giving them a forum in which to explore the interdisciplinary connections that are naturally fostered by a diverse curriculum.

The remainder of this paper presents more details of the lab projects we have developed for use in this practice-integrated curriculum.

Freshman Year

The freshman year experience for mechanical engineering majors traditionally comprises core courses outside of engineering such as math, physics and chemistry. Beginning in 2007, we introduced a new one-semester freshman mechanics course with a closely integrated laboratory instead of the classical "Sears and Zemansky"[6] course taught by our Physics Department. We designed this new mechanics course to emphasize experiential learning, including a wide variety of in-class demonstrations, weekly "peer instruction" sessions[7], and coordination of lectures leading up to and then building on the weekly laboratory exercises.

The major curricular changes for this new mechanics course were to emphasize static equilibrium, moments, and engineering applications. These changes were motivated by our recent observations of student preparedness for our sophomore-level statics and strength of materials course. A significant fraction of the students were not ready for the condensed mechanics review presented at the beginning of the statics class, struggling, for example, with the notion of moments and moment equilibrium. As we examined the (traditional) freshman physics course and reviewed course materials, two points stood out: the physics course included almost no engineering-type applications, and static equilibrium was discussed only as an afterthought. The latter point is consistent with the following fact: the classic texts in freshman physics begin with approximately 12 chapters on rigid-body mechanics, and static equilibrium is the last of those chapters. Believing that a student can begin to understand the abstract notions of forces and moments more readily in a static setting, we chose to introduce static equilibrium in the fourth week of our new course via both lecture and laboratory. Students easily handled this material and responded well, and they also enjoyed the practical anecdotes and design concepts that we introduced throughout the course. We expect those who took this new freshman mechanics course will be significantly better prepared for the sophomore-year courses.

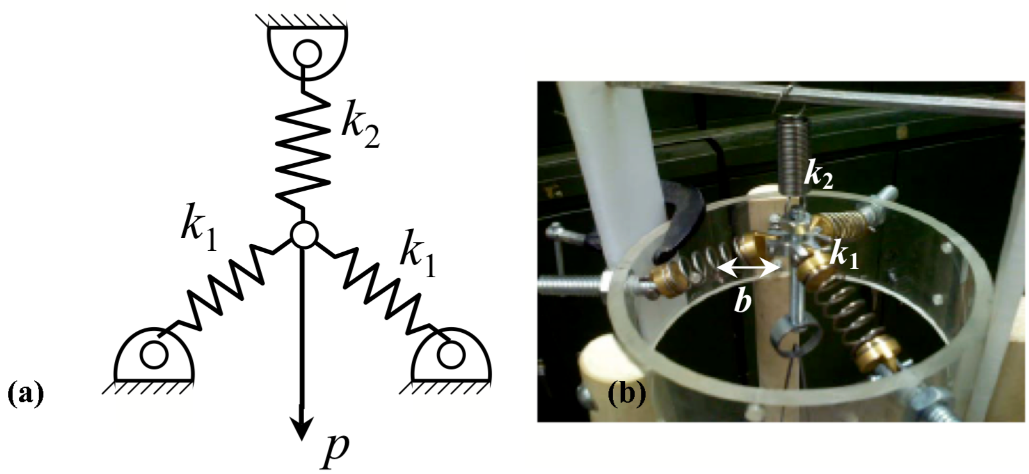

Figure 1: Snap-through apparatus. a) (Left) schematic representation of springs and load in vertical plane. b) (Right) Photo of springs. An incremental weight load mechanism (not shown) applies a downward force at the center of the spring assembly.

Novel observational experiments

Following the theme of a practice-integrated curriculum where labs drive lectures, we introduced many different engineering systems for analysis throughout the course. One nontraditional phenomenon that was introduced to accomplish several of our objectives is snap-through buckling, a problem in static equilibrium that includes bistable behavior and a snap-through instability[8]. Applications range from the keys on cell phones to tops of milk containers, which immediately drew students in and motivated them to learn about static equilibrium. The configuration we analyzed is shown in Figure 1a, and the actual apparatus we experimented with in the laboratory is shown in Figure 1b. Though it is statically indeterminate, it involves only spring deformation, with which students are relatively comfortable. Students seemed to learn a lot from that problem and especially from the associated laboratory, in which they compared the deflection behavior of the real physical system to that predicted by the theory of static equilibrium. The average student rating of the snap-through buckling lab was a 3.37 / 4.00, where a 3 corresponded to "Very Good" and a 4 to "Excellent"; for comparison, the average rating of all the laboratory exercises in MEAM 147 was 3.15 / 4.00.

To reinforce the concepts of static equilibrium and emphasize the importance of moments, we later introduced a class of problems that involved rotational equilibrium, including lab exercises on tipping and moment-induced buckling. To bring in more advanced engineering topics, we presented a module on the deformation of elastic rods with stress, strain, and Hooke's Law, another topic area that is absent from classical freshman physics. Lastly, we sought to excite students about engineering and technology by regularly using a new camera-based motion capture system to analyze the motion of dynamic systems such as a mass-spring oscillator and a bouncing ball. We are encouraged by the anecdotal evidence of the success of this new effort, and we hope our practice-integrated techniques may prove useful for the formation of new mechanical engineering curricula at other institutions.

Sophomore Year

MEAM 211 is a introductory dynamics course that anchors our sophomore curriculum, similar to those in other universities. It can be difficult to keep the students engaged in this class because they do not find the basic concepts (rigid body dynamics, equations of motion, free body diagrams, and Newton's laws) new, and many perceive the material as being a repetition of the traditionally taught freshman physics course. We have yet to see the effect of our new engineering-focused mechanics course on MEAM 211, but we hope it will enable us to teach more unique and advanced content to the sophomores.

The projects in MEAM 247 that are aligned with MEAM 211 are designed to center on real-world systems such as sports balls and trebuchets. By focusing lectures on real dynamics projects, we have found discussing the design of practical systems and their application motivates the students to ask questions and be engaged in class. Furthermore, this top-down approach allows all the concepts (including analytical ones) to be taught in the context of the systems, their design, and their applications.

Progression from observation to construction

While the projects introduced in the freshman year were primarily observational, experimentation and theory matching, sophomore year introduces more construction, including both theoretical, numerically simulated models as well as physical prototypes. One set of projects centers on the dynamics of a projectile and focuses on particle dynamics, formulating equations of motion, forward and inverse dynamics, and solving the equations of motion numerically. We have successfully used a guided cruise missile and a soccer ball subjected to three-dimensional aerodynamic forces, with simplified equations for lift and drag, to motivate questions of analysis and design in simulation using MATLAB.

Several labs also go beyond simulation, building physical mechanisms and machines. Students have analyzed and designed a water sprinkler (worm and/or planetary gears and four-bar linkages), a van door mechanism (four-bar linkage), and an elliptical exercise machine, in each case building scaled prototypes using a laser-cutter. These projects allow us to focus on kinematics and geometry and motivate students to become familiar with analytical and computational tools for planar position, velocity and acceleration analysis.

The elliptical exercise machine 3 week project included measurement and analysis of existing machines in the student gym (an example of utilizing existing equipment that both saves time from building custom lab setups as well as ties the project closer to students' lives and activities outside of class). Prior to designing and building the exercise machine the students had a short lab on electronics and instrumentation. They used these new skills to construct goniometers that measured the leg joint angles (hip and knee) of a student team member as he/she walked. This data was then analyzed (Figure 2a) and used to design and construct a new personalized elliptical exercise machine (Figure 2b) exposing the students to a third design topic: human factors and user interface design. The project introduced constrained design elements. For example, the students were given methods for four bar linkage synthesis, but specific parameters and ultimately functionality was left open.

Towards the end of the sophomore year, we have introduced a project that couples the dynamics of projectiles with kinematics and force analysis in designing and building a trebuchet. One incentive to motivate students in labs like the trebuchet is competition. In this lab, the students build gravity-powered trebuchets in a contest to see which device throws an object the farthest while being constrained in size and total weight. One failure mode that students discover early is the fracture of long lightweight arms. In order to alleviate this, a lab during the previous semester concurrent with statics and strength of materials (MEAM 210) focuses on optimally designing, building and testing to failure a truss beam with the goal of making the lightest beam that can support the largest cantilevered weight. These many practical projects enliven the sophomore-year curriculum and prepare students for more advanced endeavors.

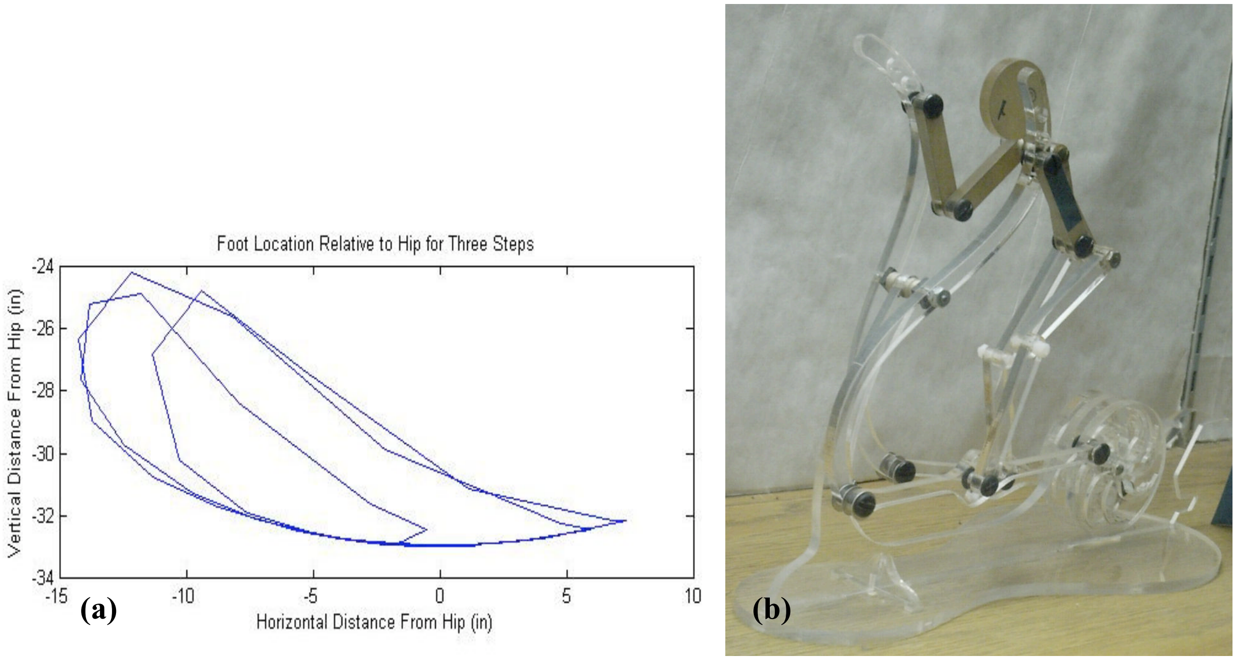

Figure 2: Personalized elliptical exercise machine, a sophomore team lab in MEAM 247. a) shows the ankle path from measuring a student's joint angles (hip and knee). b) Sample scale model.

Junior Year

During the Fall of our junior year, the lab course (MEAM 347) is concurrent with lecture-style courses in Fluid Mechanics (MEAM 302) and Vibrations (MEAM 321).

Early in the semester, it can be difficult to run suitable lab projects before the students have been introduced to any fluids or vibration concepts. So we use that opportunity to teach other important topics not taught in our core courses, such as engineering ethics, electronics, and DC motor characterization and utilization.

In the motor module, lab students are taught about motor performance and efficiency curves, then given the task of designing and constructing a high-efficiency elevator from LEGO parts and either one or two DC motors. In the past year the project was cast as a competition where the lowest energy usage device wins a prize. Students quickly discovered the values of successive prototyping, system identification, and general mechanical engineering principles including friction, gearing, and motor fundamentals. Within the first week of the project, most of the teams realized that they would need to characterize the power and efficiency of their specific DC motors; however, none of this data was available to them a priori. As such, the groups devised various methods to test their motors, with most teams hanging small objects (nuts, bolts, pens, etc.) off a pulley attached to the motor shaft and measuring the time it took for the motor raise the weight. From this data, teams were able to compute the point of maximum efficiency for their motors and then design the gear train of their elevator to operate close to this point. One particular student comment highlighted how well this self-discovery process helped them to actually understand the complex physical relationships. As the first lab of the Junior year, students were initially hesitant, but ultimately excited, by the amount of design freedom and the ability to discover methods and achieve results on their own.

Progression from construction to exploration and experimentation

The fluid mechanics topics selected for Fall of 2007 were *Surface Tension*, *Stokes' Drag*, and *Fluid Mixing.* The first two topics were based on a vast body of literature and are traditionally used in undergraduate laboratories. Following the top down teaching approach, the students were first exposed to the examples in the lab before the concepts were introduced formally in the concurrent Fluid Mechanics class. The last topic, *fluid mixing,* is a more industrially relevant project, which is rarely covered in standard fluid mechanics courses.

The *Surface Tension* module was comprised of three experiments: (i) Faraday Waves, (ii) Hydraulic Jumps, and (iii) Bubble Columns. Students were first shown the phenomena and given access to the basic theory. They were then told to generate new examples of the phenomena in an open-ended fashion, given ample freedom to experiment with many variables such as fluid viscosity, surface tension, and flow rates. Although all parameters can be easily understood in terms of dimensionless numbers such as Reynolds, Capillary, and Froude, students *with few exceptions* (~5% of the class) chose the 'turning knobs' approach. In this approach, students preferred to play with as many variables as possible before committing to an experimental strategy. This approach proved to be a very frustrating experience for the students since the number of possible combination of variables makes data analysis an overwhelming task.

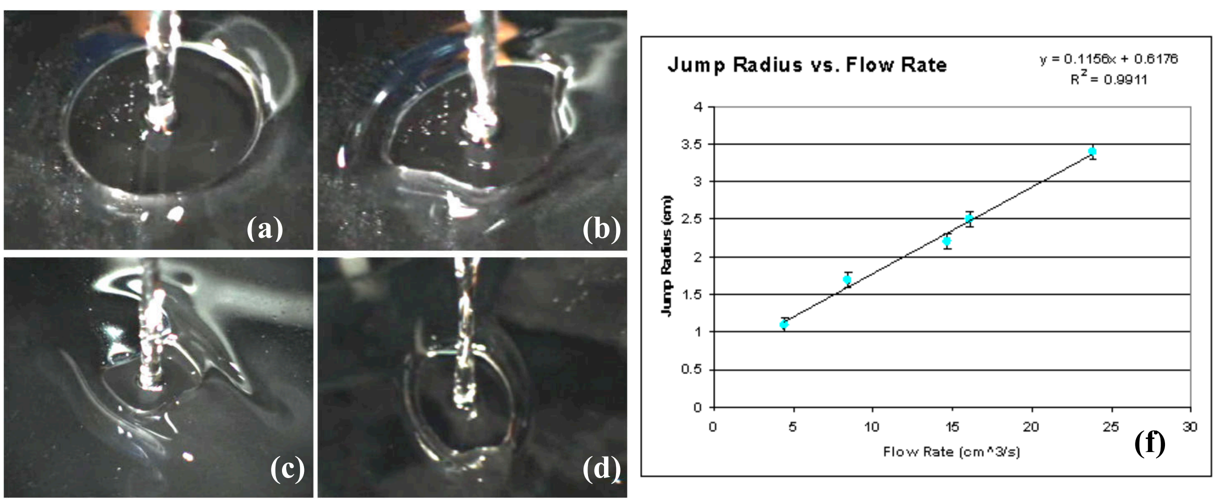

Figure 3: Students discover hydraulic jumps using a viscous fluid. Circular (a) Polygonal (b, c, and d). (f) Sample data from MEAM 347 students on radius of the hydraulic jump as a function of jet flow rate.

Nevertheless, many students were able to produce very interesting and aesthetically beautiful results, as shown in Fig. 3, for the hydraulic jump experiments. By exploring with the available parameters, students were *able to discover* new patterns in the jump structure, from a typical circular structure Fig. 3(a) to polygonal shapes Fig. 3(b)-(d). Quantitative experiments were also encouraged. Students were asked to measure the jump radius (for the circular pattern) as a function of the impacting jet velocity. Sample data from a student group is shown in Fig. 3(f) found that jump radius increases linearly with the jet velocity or flow rate.

Next, we moved to a more constrained laboratory experiment, the *Stokes' Drag* module. This module involved measuring the viscosity of an unknown fluid using a falling sphere and an understanding of Stokes' Drag. Theory was provided during a pre-laboratory recitation and students were able to check their results against tabulated data available in the literature. Every law has its assumptions and limitations, including Stokes' Drag. Students were driven into unknown waters when asked to provide and quantify experimental evidence of these failures. Again, students resorted to the 'turning knobs' approach even though the rigorous theory was provided in lecture. This time, however, students abandoned this trial and error approach after only a few experiments. They turned to the literature and performed preliminary calculations that guided them into performing more accurate experiments. Students were able to provide good quantitative and qualitative data for the Stokes regime. They also provide excellent data on the breakdown of Stokes' regime. The students' level of frustration was low, but so was the excitement.

Finally, students studied a very industrially relevant problem: *Fluid Mixing in the Laminar Regime*. Since this is an experiment with a large parameter space, students were limited to only three trials. Although this module is by far the most complex assignment, the trial number limitation proved to be very beneficial in deterring students from the 'turning knobs' approach. Students prepared in advanced and did extensive reading before attempting an experiment. The experimental data was high quality, student understanding of the problem was good, and their motivation was very high. The success of this lab is probably related to the its relevance to industry and everyday life, as noted by many students in their feedback.

Lab on designing experiments

Another module we have run twice in the Junior year is a lab on thermal conduction. The students are presented with a scenario where they are members in a fictional company called MEAMiPod. They must find the best cooling solution (measured in dollars per watt of cooling) for removing heat generated from a high power electronic component (the new fictional iPod-like device). They are given an assortment of heat sinks of different configurations, materials, and prices and are assessed a cost penalty that increases with component temperature. This exposes the students to aspects of multiobjective optimization (maximize cooling, minimize cost) that are typical of real-world engineering situations.

To push on independence, the students are not told what experiments to do, nor how to do them, though they are supplied with the theoretical background. There are too many variations to experimentally try every option, so they must decide which experiments to do using theory. As part of the exercise, the students are also taught about the structure and importance of memo writing (supported by the university's Engineering Information and Communication (EIC) group). The report they write up is not a formal lab report, but is instead a company memo indicating their findings.

Practice of Independence

The junior year includes one project that is independence focused. The students receive no procedure, no background information and no indication of where they should find the answer. They are presented with a problem they must solve and left to their own devices. In one case, *the* *vibration absorber*, the problem was the creation of a passive device that attached to a system that vibrated sinusoidally at a specific frequency. The attachment mechanism needed to steady the motion of a device attached to the moving frame. The students were encouraged to ask anyone they wanted, though it was fairly obvious that their vibrations professor would be a good resource.

Results and Conclusion

To gauge the efficacy of the new freshman mechanics program, we conducted a standardized assessment of student beliefs about mechanics principles at the beginning and end of the semester. Our students' average starting score on the Force Concept Inventory[9] was 22.7 out of 30, with a standard deviation of 5.8. The average ending score was 25.7 with a standard deviation of 4.4, which corresponds to a 40% average normalized gain for the class. This improvement corresponds well to the gains that are typically achieved by students in classes that emphasize "Interactive Engagement" through hands-on activities and active discussions[10]. Encouraged by these initial quantitative results and the enthusiastic response of our students, we are pleased to be able to share the details of our approach and further improve it for subsequent years.

During the sophomore labs the students were eager to apply creativity in the constrained design/ pattern synthesis labs. However, the times spent on the labs increased substantially; 3 to 10 times that spent during the freshman labs. We employ a 24-hour 7-days a week policy to the lab hours, so students often spent many late night hours there. The increased time spent in the lab was universal as the freedom, open-endedness and independence increased. While many students reveled in these new opportunities and increased relevance, some did not appreciate the lack of structure, and often their increased amount of time was spent inefficiently exploring paths that did not lead to successful conclusions.

One of the philosophies of these courses is that failure is important to the learning process, and in fact, more can be learned through failure than through success. The more open-ended design problems give many opportunities for the students to fail. While the learning may be increased, the frustration level typically increases as well.

Juniors in MEAM 347 initially showed difficulties in dealing with open-ended laboratory assignments in which the main goal is to study fluid mechanics phenomena, even though theory is readily available. In such cases, they had a tendency to use the 'turning knobs' approach, in which they experiment with many parameters without a goal in mind. This approach leads to a high level of frustration since data analysis becomes an overwhelming task. Nevertheless, self-motivated students were able to provide high quality results, mostly because they prepared in advance (via preliminary calculations) and sought out a feasible experimental strategy. On the other hand, when laboratory experiments were constrained by the number of trials, most students performed very well, with low levels of frustration, even though the experiment was more complex. The limitation in the number of trials forces students to better prepare for the experiments and is a practice we intend to continue.

One semester, the juniors in MEAM 347 were surveyed and asked the question "True or False, I learn more from MEAM 347 than in any other class." 51% of the students responded True.

Many who responded False commented that while the lab course worked well, there were other courses that performed better. That more than half the students believe that they learned more in a lab than in any other class, is a powerful statement, though it doesn't actually mean that they did learn more in the class. The idea that the concepts get ingrained in the labs (even if they were learned in theory classes) is consistent with the results of this survey.

Student feedback from seniors and juniors who have experienced the transition has been almost universally positive. Examples of student feedback include:

> "The lab-based approach really does promote a more thorough understanding of the material in my opinion. It also excites the students as they have tangible final products […], especially in comparison to more theoretical classes."
>
> "I think the curriculum's emphasis on labs gives a good amount of exposure to a lot of different possibilities within mechanical engineering in terms of work opportunities."
>
> "Of course, there's also a downside to this. […] lab-based classes really fill up a student's schedule. […] Therefore, I just think you have to be careful about overloading the students."
>
> "[…]keep doing what you're doing. I think it's working wonders."

One of the overall goals in developing PIC was to attract students to MEAM and maintain or increase enrollment. During the four years that this curriculum has been phased in, the enrollment in our MEAM department has steadily increased from 135 to 193 an average of 14% each year. We look forward to continuing to improve our curriculum over the coming years

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