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The Mechanics Project: A Pedagogy of Engagement for Undergraduate Mechanics Courses

Prof. Keith D. Hjelmstad, Arizona State University

Keith D. Hjelmstad is President's Professor of Civil Engineering in the School of Sustainable Engineering and the Built Environment at Arizona State University.

Amie Baisley, University of Florida

Amie Baisley is a lecturer in the Department of Engineering Education at the University of Florida. Her teaching and research interests are centered around the sophomore level courses that engineering students take and how changes in those courses can impact student learning and retention.

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Abstract

The Mechanics Project was founded just over eight years ago at a large R1 university in the southwest. The objective of the project was to improve the learning experience in the sophomore level mechanics courses (statics, dynamics, and deformable solids). We have designed and implemented an engaged learning environment that encourages students to discover and explore the foundational engineering concepts in these courses more deeply, emphasizing 'why' as much as 'how' in the learning process. The courses associated with *The Mechanics Project* are designed around two-week modules that comprise four active recitation periods, one lecture, and one assessment. Most of the class time is spent in a highly engaged student-centered recitation environment, staffed by an instructor and a team of undergraduate teaching assistants. This structure allows the students to have a more individualized learning experience in a supportive environment. The frequent assessments make examinations less stressful and mastery-based grading allows each student to monitor their progress on achieving the individual course learning objectives. A course survey, administered each semester, shows a high level of student satisfaction with the instructional elements that make up the course structure. This paper describes the details of the course design and document some of the outcomes.

Introduction

We have embarked on an effort to change the educational outcomes of engineering students by changing how we teach the foundational engineering courses. We call the effort *The Mechanics Project* because, at least initially, the focus has been on the engineering mechanics courses (Statics, Dynamics, and Deformable Solids). *The Mechanics Project* was created at a large R1 university in the southwest, and although it was certainly not the first effort in higher education to redesign the fundamental mechanics courses [1] – [6], it has created long term impacts on both student learning and subsequent course content.

The decision to focus on sophomore-level foundational courses emanates from a set of observations about student learning and a gnawing sense of frustration shared by many faculty members across many different institutions that we are failing to make the most of an extraordinarily important time in a student's development. We are failing to bring enough students to full fluency with the concepts that underpin many of the technical ideas that engineers use to solve problems. Furthermore, there is a growing concern that the pedagogy neither embraces current technology—both in teaching and in professional application—nor does it adequately embrace what is now known about how people learn [7] – [9].

The foundational mechanics courses are generally taken by engineering students in their sophomore year of college. These courses serve as a bridge between the math and science of the freshman year and the engineering application courses in the upper division in civil, mechanical, and aerospace engineering (and others). The role of the mechanics courses in the context of a typical civil engineering curriculum is illustrated in Fig. 1. The first course, Statics, is generally calculus based and is prerequisite to both Dynamics and Deformable Solids. To limit the backlog of prerequisites, Statics is usually taken concurrently with vector calculus (Calc III). The mechanics courses serve as a foundation for almost all of the civil engineering core courses (e.g., structures, geotechnical engineering, and fluid mechanics), and those core courses serve as the steppingstone to advanced professional courses in the discipline. Other curricula rely on the mechanics courses in a similar way but have a different disciplinary core at the junior level and different professional courses at the senior level.

The three courses are generally associated with three semester credit hours each. At the rise of *The Mechanics Project,* these courses were taught in a lecture-based format that met twice a week using common mechanics textbooks. We will refer to this context as the "traditional" learning environment, which is comprised of lecture during class time, homework outside of class, and a few exams to assess learning.

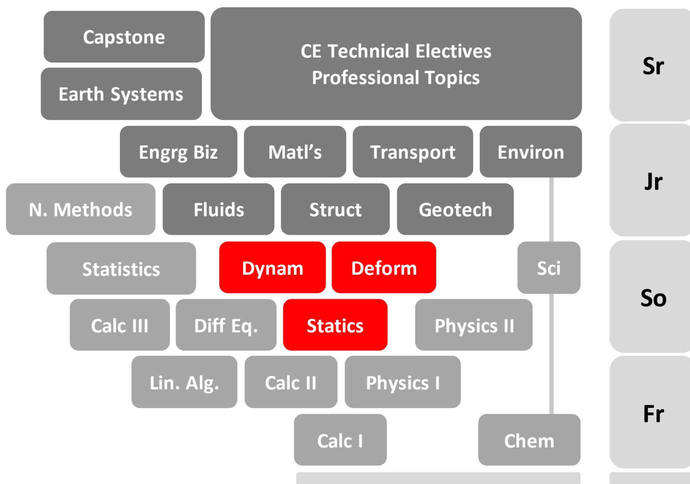

Fig. 1. *The Mechanics Project courses in the context of a curriculum.* The curriculum shown is a typical civil engineering curriculum, including math and science foundations, followed by mechanics courses (Statics, Dynamics, and Deformable Solids), followed up upper division courses. Note that only technical courses are shown.

The mechanics courses were an interesting choice for educational reform because there was little debate about the importance of the topics. Initially, the redesign challenge focused on establishing more effective pedagogical strategies. The goal was to teach the standard content better along with embracing current technology, so that students would emerge from the early mechanics courses as more successful problem solvers. An initial literature search made it clear that the traditional mechanics courses were not embracing educational research or what has been learned about how people learn [7] – [9]. These ideas became central for the new course design. The faculty agreed to the following design principles:

1. Consider the mechanics courses to be *one thing.*
2. Consider the faculty associated with the mechanics courses as an *instructional team*.
3. Clarify the objectives of each course. Connect assessment to the objectives.
4. Lecture less. Assess more.
5. Provide a supportive learning environment for students.

In most institutions, individual courses are viewed as the private domain of the individual instructor. Design principles 1 and 2 break that mold and consider the teaching of all three courses as a coordinated team effort and need to build in features that would sustain those principles. In support of design principle 3, we sought to find a granularity in the stated course objectives that would allow tight correlation with the assessment process [8]. The ideas of design principle 4, to lecture less and assess more, has been supported in much of the literature [8], [10]. Also, there are benefits in moving away from traditional grading approaches and there is evidence that doing so can improve student learning [11].

Design principle 5 was both an answer to the question, “What do you do with class time if you lecture less?” and an acknowledgement that students who progress at different rates are grafted onto an experience that progresses at a fixed rate. We wanted a structure that keeps the students who progress faster engaged while still offering the opportunity to attend to the needs of the students progressing more slowly, or who bring deficiencies from prerequisite courses with them.

What we found upon implementation of the pedagogical ideas was that changing pedagogy was not enough. There is a marriage between pedagogy and content that deserves attention. Case in point for *The Mechanics Project* was the role of computing in the learning environment. There had been no computer programming in the traditional approach to these courses, but that omission seemed more like an anachronism than sound pedagogical design. So, in our redesign of the courses, we included some significant shifts in content where modernization asked for it.

The courses designed as part of *The Mechanics Project* had several overarching goals: (1) Focus on ‘why’ as much as ‘how,’ by getting the students more involved in derivation, (2) promote exploration and discovery as a primary learning avenue, and (3) embrace computing as a means of understanding the basic concepts. Overall the aim is to better facilitate mastery of the concepts and to develop self-driven learners.

Course Structure

The course structure that emerged from the design process is a hybrid environment in which all students assemble in a lecture hall once per week, one week for a lecture and the other for an exam. In addition, the students meet in smaller sections in a flipped recitation environment focused on group problem solving supported by the instructional team. This design maximizes the opportunities for the students to interact with the course content and instructional staff during all the different course aspects. It also achieves the design objective of lecturing less.

The outline of the course design is illustrated in Fig. 2, which shows that the course is divided into seven modules, each of which covers two weeks. The anatomy of a typical module shows the main features: Three recitations (Rec. *n*), one lecture (in the middle of the module), one rehearsal exam (RE), and one module assessment (MA). The recitations and rehearsal exams are 75-minute sessions held in smaller rooms. The lecture and module assessment are 50-minute sessions held in a large lecture hall.

Recitation. In the recitation periods, the students work through the “problem(s) of the day” in groups, with the instructor and undergraduate teaching assistants (UGTAs) providing support, asking probing questions, giving advice, and generally activating the learning environment, as needed. The recitation problems advance the learning objectives of the module and need to be challenging enough for the students to see the benefit of working in the presence of the instructional team (as opposed to finding logistical benefit to skipping class) and to generate peer teaching as the course develops.

After a brief introduction of the concept behind the problems, the students get to work. The students come back together for the last 10 to 15 minutes of the class period and the instructor goes over the solution to the problem, pointing out things observed during the session. The solution is posted on the course website, and the students are encouraged to go over it within 24 hours to gain the most benefit from connecting their own efforts with learning from the solution as an example.

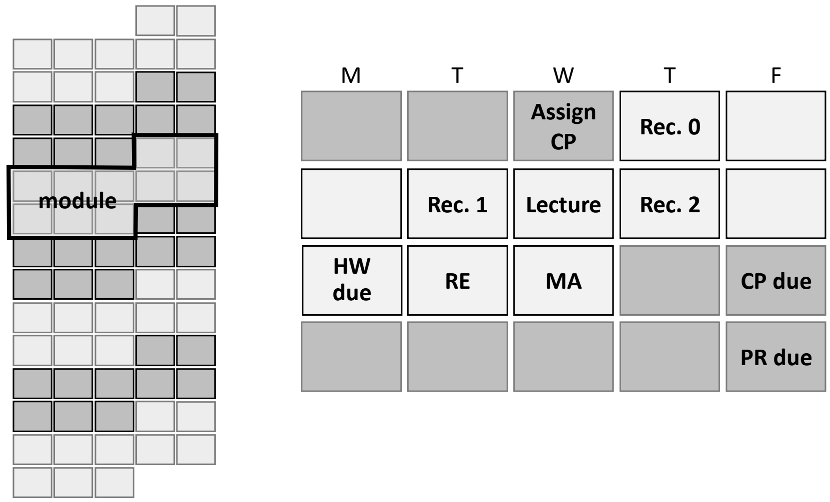

Fig. 2. *Anatomy of a module*. A module is a two-week period with three recitations (Rec. *n*), a lecture, a rehearsal exam (RE), and a module assessment (MA). In addition, a computing project (CP) is completed during that period. A semester comprises seven modules.

The first two recitations of the module occur before the lecture. Course materials are available to the students (course notes and examples) and the students are advised to prepare for recitation by studying these materials. The recitation design accommodates the students who prepare well while at the same time making learning progress possible for those who do not. In fact, it is not uncommon to see a student pop open the notes or an example in response to seeing the problem of the day. While it is not possible to get every student to prepare in advance, it is possible to create a structure that does not fall apart if they do not prepare. Trying to solve a problem before getting direct instruction helps to develop self-driven knowledge acquisition.

One of the most valuable aspects of this environment is that students can work at their own pace and have the immediate support they need when they are struggling with a concept. The students are free to approach the problem(s) during recitation any way they want (and if there are multiple problems, in any order they want). One measure of success in the engaged learning environment is the noise level. A classroom with 40 students is a beehive of activity with students talking to each other and to the instructional team. Almost all students remain engaged throughout the 75-minute session, with a high percentage of time on task.

The instructional team comprises one instructor (and sometimes two, depending on the size of the recitation) along with 2-3 UGTAs. A ratio of students to instructional staff of about 10:1 works very well, with little latency in attending to student needs. The UGTAs are provided with very detailed solutions of each recitation problem, so they can have confidence in answering student questions. If a UGTA is unable to address a question, they can bring the instructor in for a consult. Most questions do not require the higher level of knowledge, so this is an excellent way to leverage the instructor.

Lecture. The single lecture in each module is done in a standard in-person lecture format but is delivered as a team of two lecturers. The students have already read, learned, struggled with the material and are familiar with it, so the lecture focuses less on the details of the concepts but on the big picture of the module and where it fits in with the rest of the course and the larger context of mechanics. The lecture takes place in a regular large lecture hall with all students present. The students enjoy the lecture because it is a learning environment they are accustomed to, and since they have already been exposed to the material they are encouraged to sit back, *not* take notes, and think about what is being said. We employ some active learning techniques in lecture.

Rehearsal Exam. The rehearsal exam (RE) is held in the recitation room with the problem of the day delivered on paper, similar to an exam. The students spend the class period solving the problem and do peer grading at the end (to familiarize them with the grading rubric). The problem is the same level of difficulty as the module assessment, so it serves as practice (hence the name 'rehearsal'). The rehearsal exam environment is the same as recitation—the instructional staff are all there, students work in groups, and students can use their notes and examples.

The last 10 minutes of the rehearsal exam period are spent peer grading another student's rehearsal exam. The students exchange exams with their peers and grade while the instructor discusses the solution to the problem. The students are given guidance on how to grade the exam. The peer grading is an important component of the course to provide the students with an opportunity to understand the grading process, see the solution discussed, and receive immediate feedback to prepare for the assessment.

Module Assessment. The module assessment (MA) takes place in the large lecture hall on opposite weeks from the lecture. This is the final session of the module. The exam is a standard individual assessment. A standard crib sheet is provided. The module assessment is a single problem that activates some (usually not all) of the course mastery objectives. Because there are seven module assessments, it is possible to build in the redundancy needed to operate a mastery-based grading system.

Course Topics

The implementation of two-week modules created the need for each module to have a topical theme. The topics covered are basically the same as most courses on these subjects that are taught in the traditional framework. That is important for course articulations, especially for lower division courses. The mastery objectives serve as a more important organization feature than the topics and frame the solution process for all topics. The various small and unique problem types related to each topic are dispensed through the problems of the day in recitation. For example, the notion of 'radius of gyration' comes up in a recitation problem, and when it comes up, the recitation environment is the time and place it is discussed. The module topics provide a framework for organizing the course notes, problem selection, and lecture content. The modules for each course are given in Table 1. This table suggests that the topical coverage of these courses does not deviate substantially from other courses with the same name. However, depth of coverage is somewhat greater than most traditional courses.

Table 1. General outline of module topics for the mechanics course sequence. These topics are like almost all courses in these subjects taught in a traditional lecture-based format.

Module	Statics	Dynamics	Deformable Solids
1	Equilibrium	Particle kinematics and kinetics	Axial bar
2	Self-weight	Work and energy	Multiaxial states of strain
3	Distributed loads	Rigid body: mass along a line	Multiaxial stress and const. laws
4	Hydrostatic pressure	Rigid body: mass over a volume	Beams: Equilibrium and stress
5	Trusses	General planar motion	Beams: Deformation
6	Frames	Vibrations	Beams: Indeterminate problems
7	Internal forces	Lagrangian mechanics	Torsion

Implementation

The implementation of *The Mechanics Project* across the three constituent courses was done over a period of three years, as illustrated in Fig. 3. By accident of history, we implemented Dynamics first. In one semester, we put in place all four of the major changes of (1) moving to the flipped recitation using UGTAs and one lecture per module, (2) creating course materials—notes and examples—that allowed (3) the implementation of mastery-based grading, and (4) the introduction of computing projects as a major component of the course. A year later we hoisted up Statics, and a year after that Deformable Solids.

While not part of an intentional plan, there was some advantage to working through Dynamics before Statics. For example, many of the notational decisions were made to support the derivation of equations for dynamics that may seem optional for statics. Students generally struggle with mathematical notation, so introducing concepts in Statics in preparation for Dynamics and Deformable Solids is important. Also, the imperative of introducing computing projects is more acutely felt in Dynamics. Traditional courses tend to make dynamics more like statics by framing all problems as 'snapshot' problems (e.g., with problem statements that ask to evaluate the equations of motion at a specific time, most often $t = 0$). Starting with Dynamics allows us to reverse that thinking.

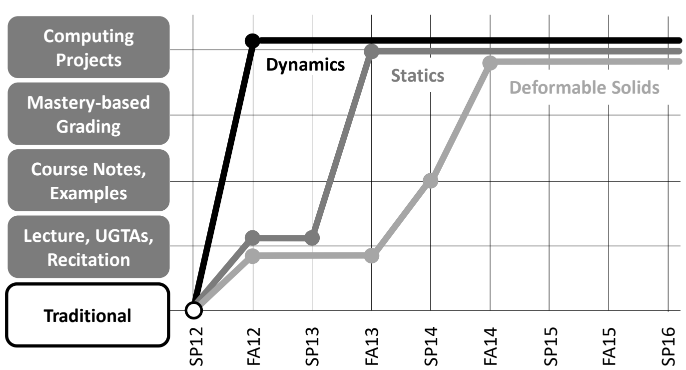

Fig. 3. *Implementation of the three-course sequence*. The SP12 semester was the last offering of all courses in the traditional framework. Each of the three courses was brought to full implementation of the new framework in each of three successive years (with some efforts in Statics and Deformable Solids prior to their main implementation year).

Mastery-Based Grading

Students are driven by grades. The topic of student motivation has been studied extensively and students make many of their decisions through the lens of the grade-driven environment [12]. In our own teaching experience, we have found that there appears to be an addiction, of sorts, to scoring. In the traditional grading system (where you get a score on a test or a grade at the end of a semester), it is usually impossible to reverse engineer a student's grade to discern what they have mastered. We wanted to design a system of evaluation and feedback that at least blunted some of the negative impacts of traditional grading. The result was a mastery-based grading scheme, the details of which is the subject of another paper [13].

The mastery-based grading system is based upon redundant demonstration of the ability to achieve certain outcomes set in each course. To make the mastery-based system work, each course had to create a set of problem-solving objectives that could be repeatedly assessed. These objectives are different than the module topics, as they are the continuous strands that span across all topics. The course objectives are different for each of the three classes but include objectives like Free body diagram, Force equilibrium/Balance of linear momentum, Compute relevant response, etc. For example, the ability to *draw a free body diagram* is not particular to one type of mechanics problem but is common to all and shows up as an objective required in every module. On the other hand, *torsion* is a specific type of problem that is the focus of a single module. Once identified, this set of objectives creates a template for solving problems in the course. All of the examples and recitation solutions are organized around the mastery objectives, and students are asked to organize their work this way, too. The module assessments are graded objective by objective individually using the following rubric options: (a) complete and correct, (b) correct but with small calculation error, (c) minor conceptual error, (d) major conceptual error, (e) no evidence shown. Each objective of each problem is weighted in accord with the difficulty presented by that problem. Hence, each problem contributes a different amount of progress toward mastery. In order to work, the assessment opportunities must be frequent and must include high-quality problems designed to activate multiple objectives.

A student must demonstrate multiple times—on different days on different assessment problems—that they can accomplish the objective completely and correctly. The goal of the student is to master all the objectives by the end of the semester. This is accomplished by demonstrating the required number of complete and correct showings on different assessments to add up to mastery in each objective. They generally have twice as many opportunities available throughout a semester as are required to demonstrate mastery. That way they can have a bad day and still eventually master the objective. Students like this system because it is a non-negative grading system (i.e., there is no such thing as negative progress).

The assessments take place every two weeks which result in seven module assessments during a regular semester. In addition, the final exam is now structured as four module assessment problems. The objective of the final exam is to complete their mastery demonstration of any remaining objectives not yet mastered. The students select which final exam problem(s) to work on. At the end of the semester, a portion of their grade is based upon the number of objectives mastered.

The mastery-based grading system drives the development of a solid problem-solving approach as students constantly view their learning progress through the lens of the mastery objectives. The assessment system has also changed the mentality students have towards exams. The high frequency of assessment has made each one less stressful. Doing something wrong is not viewed as 'bad' but rather a lost opportunity to make the demonstration of mastery. Thus, students can fail and learn from those failures without those failures becoming an anchor to drag around all semester. Up through the final, opportunity to demonstrate mastery always exists, and students are motivated to continue to try to master every objective.

Feedback

The mastery-based system has also changed how feedback is given to students. There are no grades or percentages given throughout the entire semester, instead a bar chart that shows how a students mastery is progressing in each objective is provided. Following every module assessment, the students are given a letter and a dashboard like the one shown in Fig. 4.

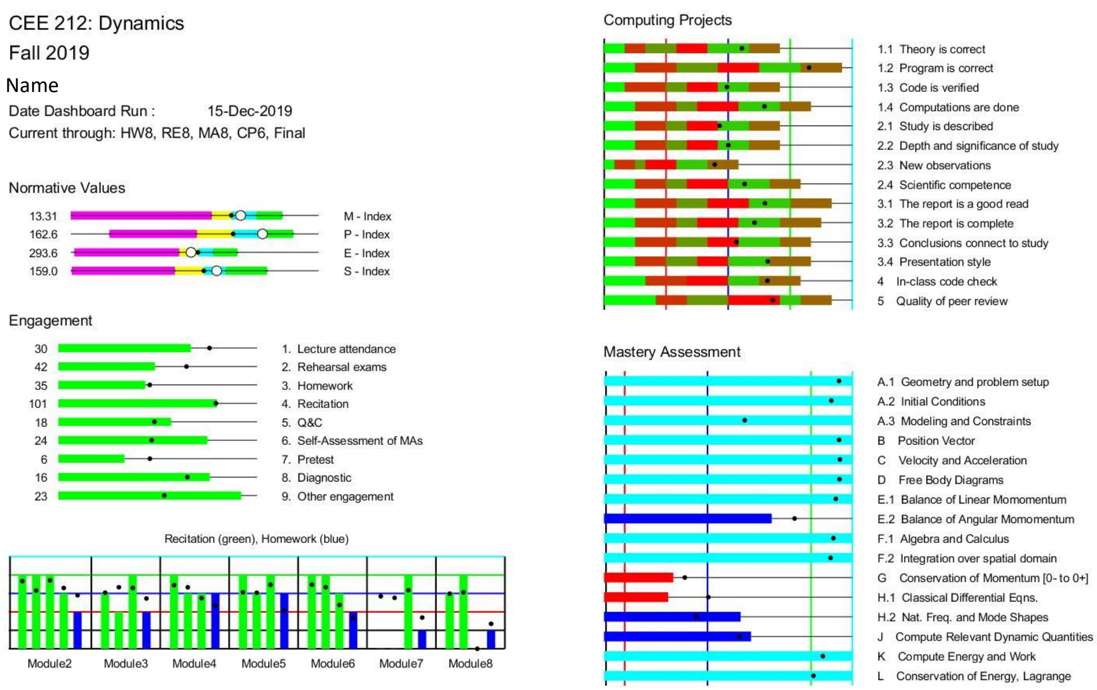

Fig. 4. *Student feedback.* The dashboard is the mechanism for giving feedback to students. It includes all of the work they have done, from showing up to lecture, to homework, to computing projects, to mastery assessment. This specific case shows the dashboard for a student at the end of a semester.

The letter provides a detailed, objective-by-objective account on how they performed on the module assessment problem, based on the grading rubric mentioned earlier. The dashboard is a visual form of feedback that shows the students their progress in all aspects of the course, including mastery growth for each objective. Both items are given to each student about a week after the module assessment. The students can see their previous assessment performance in the letter and can see their overall course progress on the dashboard.

The aim of the dashboard is to provide the students with a full account of the work they have done in the course. It includes engagement (e.g., showing up to lecture, performance on rehearsal exams, working hard during recitation, and other course activities), an assessment of their performance on the problem of the day, the computing projects, and progress toward mastery on the course objectives. We try to avoid numbers as much as possible but do provide norming information so that the students can see how they stack up against the class average (the black dots). The normative values show where they stand in the general categories of projects (P-index), mastery assessment (M-index), and engagement (E-index), as well as an overall measure (the S-index) that lets them know where they stand overall, based on the grade formula

$$\text{Final Grade} = (\text{Mastery} + \text{Projects}) \times \text{Engagement}$$

The S-index is the right side of that equation at the current moment in time. Note that engagement is a multiplier and not an additive portion of the grade conceptualization. The engagement factor can cause a full grade point difference from the least engaged to most engaged student. The net effect is that students never feel like they are done engaging and are particularly eager to earn engagement points near the end of the semester.

The absence of scores and grades during the semester has significantly changed the conversations with students about their learning progress in the course. Students ask the question, “How am I doing?” and often still mean, “What grade am I going to get?” But the answer can now be, “I see that you still have not mastered the free body diagram, perhaps you should focus on that.” The dashboard is an extremely useful tool to point out the areas where each student is struggling and excelling to provide more individualized guidance for help in the course. No two student dashboards look the same, so the instructor can personalize each conversation with each student to suit their learning needs.

Computing Projects

The other major and new component of each course was the introduction of computing projects. Prior to *The Mechanics Project*, the mechanics courses had only included simple pencil and paper problems. There was a strong push from upper division courses and industry to develop better computational skills [14]. In most institutions, education in computer programming is relegated to a single course in the curriculum. In some, that course has become a casualty of reducing the number of credits required to earn a degree.

There were two primary motivations for incorporating computing projects in the courses. First, to do so is a step toward computing across the curriculum. To develop computational competency in students, they must view computing as a regular, go-to tool for solving problems. Introducing computing early and reinforcing it throughout the curriculum is a means to change the culture around computing. Second, mechanics today is computational mechanics. It is important to know how computations are organized to become better users of modern tools of engineering. Computation also synergizes with learning mechanics through hand calculation if the projects are well conceived. Furthermore, incorporating computing projects creates opportunity for more open-ended and design-type problems previously absent in these courses.

We require minimal background knowledge in computing for students in Statics. The coding is done with MATLAB, and part of the overall course goals is to learn the rudiments of computer programing. The coding part of the projects are designed to be progressively developmental so that the students don’t drown in syntax and logic errors. We also provide lots of support for programming. The aim in the projects is to spend most of the time exploring the topical problem using a working code that the student has written.

The students write a full report for each project, summarizing the theory, describing what they elected to study, and explaining what they discovered. The reports are evaluated using a rubric with twelve items: four associated with developing theory and writing code, four associated with exploration and discovery, and four related to the quality of the written report. The students complete four projects in Statics and six each in Dynamics and Deformable Solids. This represents a rather high workload for the courses, but the aim is to make writing code and reports seem like a normal activity.

We have seen dramatic improvement in the ability of our students both to compute and to write, as evidenced by faculty teaching the upper division courses introducing more assignments that require computing. Further, we find that our graduate students that come up from our undergraduate program with the mechanics courses described here compare very favorably with students who come from elsewhere for graduate study in their abilities to execute computing projects and communicate the results.

Engagement

The primary aim of a pedagogy of engagement is to get students engaged in their own learning. Almost every aspect of the course design in *The Mechanics Project* centers of enhancing engagement. Ideally, all engagement should be intrinsic—learning driven by curiosity and the satisfaction of that curiosity viewed as its own reward. Students are intrinsically motivated by the social environment of recitation. They enjoy coming to class. They make friends and talk to each other during class but almost all the conversations center on the problem of the day. The computing projects are designed to get to interesting outcomes. That interest is intrinsically motivating (but swims against the current of frustration inherent in programming). The reduction in stress of the exam is also intrinsically motivating (or, perhaps more accurately, absent of demotivation).

While getting to pure intrinsic motivation is the goal, it is nearly impossible to achieve. Thus, some extrinsic motivation to foster engagement is valuable. Students will do work if you value it. We provide a means of valuing simple engagement (e.g., showing up to lecture) through the currency of *engagement points*. Everything we want students to engage in, outside of the mastery assessments and computing projects, we grant engagement points for. Students earn engagement points for doing the homework problems (more for better quality), for working hard during recitation, for participating in course surveys, and other activities. The specific value of each activity that earns engagement points is documented in the course materials.

The engagement portion of the final grade is a multiplier to the mastery and computer project sum. The multiplier ranges from $0.9 - 1.1$ based on the number of engagement points that each student accumulates throughout the semester. The number of engagement points has no limit, and the multiplier can alter a student's final grade by a +/− grade.

Indications of Success

It would be great to be able to present a chart showing student achievement in mechanics before *The Mechanics Project* and student achievement after. However, in the process of implementing the new learning environment we also changed several aspects of what we wanted students to achieve in the courses, including a shift away from learning 'tricks of the trade' for speeding up manual calculations (e.g., lumping distributed effects) and toward tasks that are more consistent with improving derivation skills. Also, the new aspects, like computing projects, simply did not exist in the traditional versions of the courses. Thus, assessment of success of a project like this one is complicated.

The flipped recitation environment has afforded us an unprecedented opportunity for direct observation of student thinking and problem solving, as we work in a one-on-one or one-on-few mode of instruction. This social learning environment has also made it possible to directly observe student motivation. While not detailed in this paper, one of the authors has implemented a mechanism for soliciting student questions and comments and responding to them (to date nearly 8000 individual questions). These questions and comments provide clear insights into changes in student mindset over the course of this project (e.g., attitudes about computing). Many of the conclusions we have come to about the success of this project are built upon these direct observations of over 800 students over 12 semesters.

We do, however, have some data-based indicators that also confirm that the project outcomes are good. We present those in this section.

Student achievement of mastery objectives. The aim is to master as many of the objectives as possible. A picture of how that looks over all students in the course over twelve semesters is shown in Fig. 5. On the right, the level of mastery is represented in quartiles with the large black dot representing the median. On the left is a representation of how many opportunities to demonstrate mastery there were. The cyan line represents the amount of opportunity needed to get to mastery (i.e., it is the same as the cyan line on the right chart). Our target each semester is to provide around twice as much opportunity as is needed so that students can experience failure along the way without ruining their grade prospects. You can see that this target is achieved, on average (the open circle), for most objectives.

Fig. 5. *Mastery of objectives—Dynamics*. This chart shows the results of twelve semesters of student achievement and availability of the mastery objectives in Dynamics (n=829). The chart on the left shows the availability of the objectives, with the cyan line representing just enough to demonstrate mastery. The open circle is the average and the gray bar is the range, top to bottom. The right shows student achievement for each objective, divided into quartiles, with the median shown as the large black dot.

The nature of success under the mastery-based grading scheme is detailed in another paper [13]. However, this chart gives a sense of what mastery looks like for the student population. For each objective the population shows a range of achievement. Note that the early objectives (A-F) demonstrate a solid level of achievement. It is evident that the average student masters 9 of the 16 objectives. It is also clear that there are areas of weakness (sometimes our fault for not providing adequate opportunity). This chart shows that part of success is simply having enough opportunity to demonstrate success. It also shows how complicated the picture of mastery really is for these ideas (which is not evident in the traditional 90/80/70/60 grading scheme).

Computing progress. The computing projects are a new component in the environment, which makes progress difficult to assess. One small bit of encouraging data comes from the Fundamentals of Engineering (FE) exam results presented in Fig. 6. This chart shows a steady increase in the achievement of the students in our program compared with the national average in the area of *computing*. This improvement can generally be attributed to adding computing throughout the program, driven by the computing inherent in *The Mechanics Project*. This trend is significant as the scores in mathematics and other subjects have remained constant during that same time period.

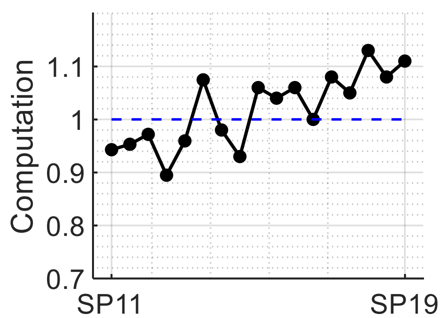

Fig. 6. *Fundamentals of Engineering (FE) results*. The *computation* portion of the FE exam results for students in our program from SP11 through SP19 show steady increase in student success on this topic compared to the national average (the dotted line).

Course surveys. At the end of each semester, a course survey is given during the final recitation of the semester. The survey asks the students to rate each component of the course based on how they liked it and how they valued it. The results have been positive overall for each semester. A typical example of those results is given in Fig. 7.

Along with the course survey, we ask the students to pick their top three features and their bottom three and explain why they made those choices. This feedback is very useful for making improvements to the courses. One thing is very clear from these results. The students uniformly like the recitation environment, and many claim their best learning experience is in the rehearsal exam, which makes sense because it is a local peak in preparation for a module and a great opportunity for things to fall into place. They generally place the computing projects and homework in the bottom and mention the workload as being rather high.

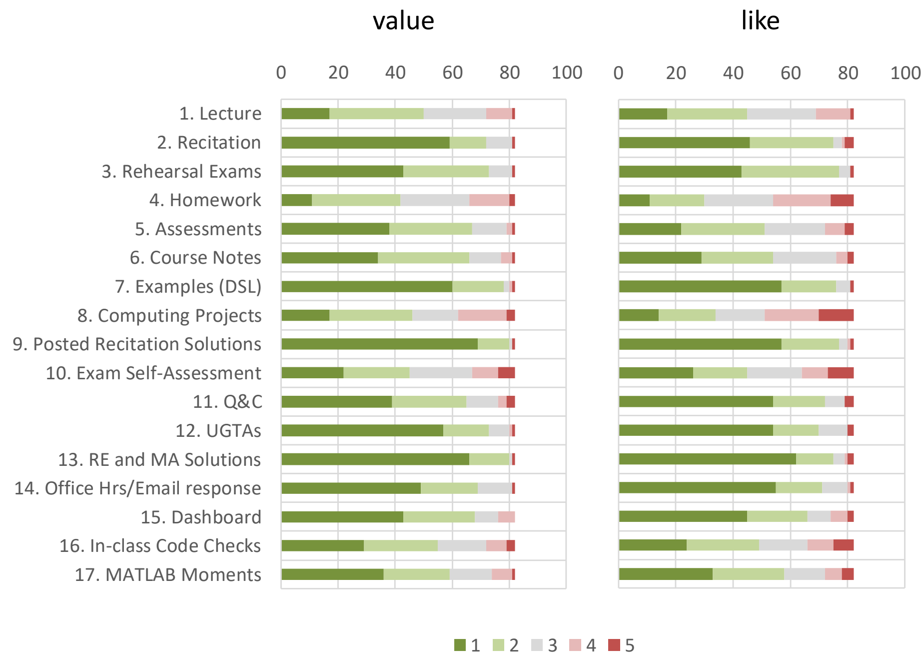

Fig. 7. *Student evaluation of course* features. Students are asked to rate each course feature on a Likert scale (1=Strongly positive to 5=Strongly negative) for how much the *value* the component and how much the *like* the component.

Twins Study

One of the most interesting outcomes of *The Mechanics Project* is the impact on learning outcomes for female students. There were two semesters at the start of the project, when Dynamics (CEE 212) was taught in the engaged format and Deformable Solids (CEE 213) was still largely executed in the traditional format. About 90% of the students were common to both courses. In essence, they were their own 'twin' in a twins study. The final grade outcome over these two semesters is shown in Fig. 8.

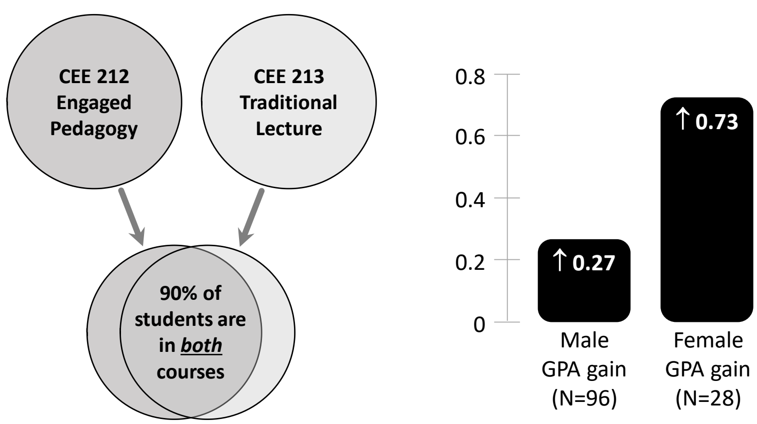

Fig. 8. *Twins study*. Over a two-semester period, students in two different learning environments were their own 'twin.' The differences in grade outcomes suggest improved learning in the engaged environment over the traditional one. The plot shows the difference in student achievement, expressed as a GPA gain of the engaged environment compared with the traditional environment.

The twins study showed that students earned higher grades in the engaged environment than they did in the traditional one. While it is possible that some of the net positive shift is due to differences in grading between instructors, the gap between female and male students cannot be explained by such a difference. This simple study does not allow us to identify which aspects of the new design might have caused the shift. There are many differences between the two environments, but it does suggest that the traditional environment might be implicitly biased against female students.

Lessons Learned

The implementation of *The Mechanics Project* did not happen overnight and was not without failure and doubt. As mentioned earlier, in the first semester changes were only made in Dynamics and the students nearly revolted. In the second semester we were able to adjust several organizational features (e.g., lengthening recitations from 50 minutes to 75 minutes). As the semesters progressed, the course materials were created and improved. Also, the culture started to shift. Students in the first semester thought of the course structure as strange because they had not experienced anything like it and no one had gone before them. In subsequent semesters, students had heard about the courses and there were upperclassmen who could attest to the values. As we recruited UGTAs, they served as ambassadors to the new environment.

In the third semester, Statics was fully implemented. One of the interesting outcomes of having Statics in the new format was that the adjustment pains expressed by students in Dynamics largely ceased (and moved to Statics). Now students coming into Dynamics had already wrapped their minds around the learning environment and it did not scare them anymore. This lesson provides great insight into how students cope with the educational environment. They depend upon their ability to predict how learning will go. Almost everyone who has implemented a dramatically different learning strategy has experienced a drop in their course evaluation. Those drops are temporary as students are quite able to adjust to new environments. The current problem is now reversed. As students move on to the upper division courses they need to adjust back to the traditional environment (and they express some dissatisfaction with that, as evidenced in course evaluations and the senior exit survey).

In the fifth semester, Deformable Solids was fully implemented. While the original idea was to redesign all three courses in accord with the design principles in the first semester, the interpretation of those principles varied considerably among the three faculty instructors assigned to those courses. The authors were assigned to Dynamics. We learned a great lesson in team formation and execution from this experience. It was not until the courses were team taught by a group of faculty members who understood and shared the value structure of the design and who collaborated through team teaching of the three courses, did the effort settle into the success it is today. We also learned that true team teaching is very helpful in bringing in new faculty and maintaining the stability of the vision.

Preparation of course materials was a heavy lift. Traditional textbooks are designed to value shortcuts over derivation and hence, do not support the mastery-based learning environment of *The Mechanics Project.* The courses dramatically improved when the readings, notes, examples, problem solutions, and projects were all consistent and mutually supportive.

We have also learned a lot about how to create a successful recitation environment. Initially, the concept of a recitation seemed simple: students work together and learn by doing. However, many factors impact the success of this environment from classroom set up, to class size, and meeting time. For example, it is essential to have a classroom with tables for group work with adequate space for the instructional team to get to individual students. Whiteboard space is an additional plus in the classrooms because groups may choose to stand and work through problems. We have found that the ideal recitation class size is between 40 and 50 students (provided the space supports that many). With fewer than 30 students, the environment is too quiet and that curbs student interaction. Above that size, a crowd threshold phenomenon occurs, and the classroom comes alive with engagement. Having more than 50 students begins to present logistical challenges for the instructional team, but the model will scale to any size provided an adequate number of UGTAs are included.

Conclusion

The engaged environment has transformed both how and what we teach in the sophomore-level mechanics courses. This change has had a significant impact on the mindset, motivation, and problem-solving abilities of the students who emerge from these courses. This change has enabled instructors of upper division courses to capitalize on the additional skills possessed by the students. The ability to individualize the learning and guidance for each student, even when dealing with large class sizes, makes this pedagogical model interesting for adoption in other courses.

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