# The Purdue Mechanics Freeform Classroom: A New Approach to Engineering Mechanics Education

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## Introduction

Motivated by the need to address the broad spectrum of learning styles embraced by today's engineering students, a desire to encourage active, peer-to-peer, and self-learning, and a goal of interacting with every student despite ever-expanding enrollments, the mechanics faculty at Purdue University have developed the Purdue Mechanics Freeform Classroom (PMFC) – a new approach to engineering mechanics education. This complete, yet evolving, course system, implemented to date in two courses: ME 27000: Basic Mechanics I (an introductory-level course in engineering statics, which serves students in numerous engineering disciplines) and ME 27400: Basic Mechanics II (an introductory-level course in dynamics and mechanical vibration, which serves students primarily in mechanical engineering), seeks to combine the more successful elements of the traditional classroom with new hybrid textbooks, extensive multimedia content, and web2.0 interactive technologies to create linked physical and virtual learning environments that not only appeal to students, but markedly improve their technical competency in foundational engineering technical areas.

Given this framework, the present work specifically seeks to describe the Purdue Mechanics Freeform Classroom, its constituent components, and, where pertinent, their development and evolution. Complementing this is a discussion of preliminary assessment, both formal and anecdotal in nature, the results of which not only highlight the group-level efficacy of the approach (as captured through student failure and withdrawal metrics), but also the high levels of student engagement and satisfaction that it yields. In addition, and in light of their importance in the presence of sustainable curricular change, issues associated with faculty buy-in and material adoption are briefly discussed. The work ultimately concludes with a brief overview and a discussion of future growth.

## Overview of the Purdue Mechanics Freeform Classroom

Though some elements of the PMFC have been in development for more than five years, the current amalgamation of educational tools has been implemented for only five semesters in Basic Mechanics I, and seven semesters in Basic Mechanics II. (Note that the durations reported here include only fall and spring terms, though the course materials described herein have been utilized in smaller summer sessions as well.) Though the content for each course was developed independently by distinct instructors, each is founded upon the same five core elements:

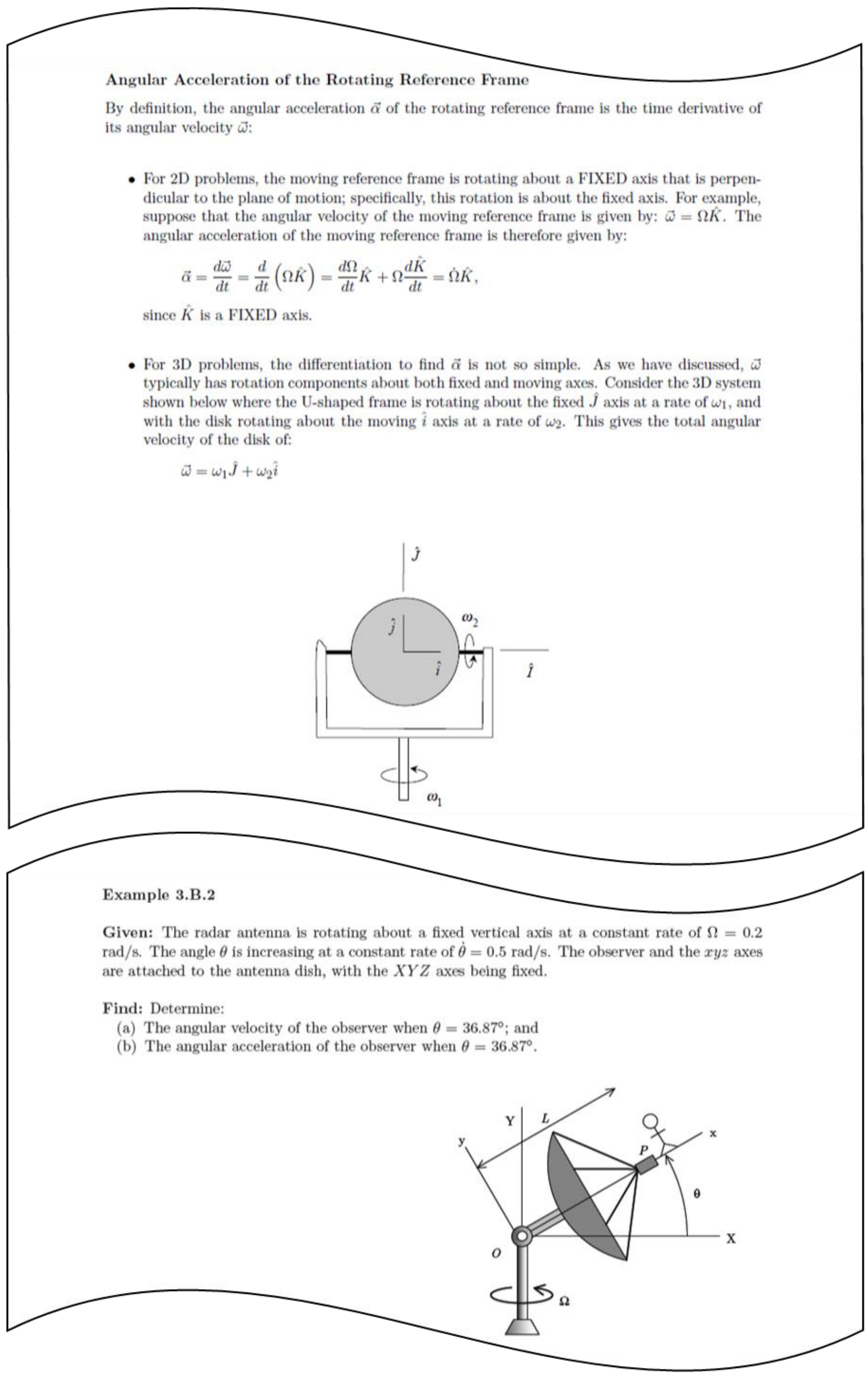
- Largely Traditional Lectures;
- Hybrid Textbooks/Lecture Notes;
- Extensive Multimedia Content;
- Course Blogs; and
- Refined Student Assessment Tools

These elements are briefly described below.

Key components of the PMFC experience are the hybrid textbook/lecture notes sets[1,2], dubbed "Lecturebooks". These hybrid texts, used in place of a traditional textbook, are designed to present the students with pertinent background information in a concise fashion, highlight fundamental engineering principles and optimal problem solving techniques, and provide an extensive array of practical and relevant examples through which students can hone their skills. The hybrid nature of these recently-authored documents (effectively more mature versions of the workbooks ably employed in elementary school classrooms) stems from the notion that most of the requisite factual information is provided in full, while brief and extended examples are provided with ample white space for student note taking. The latter allows the students to actively work example problems with the instructor's assistance, within the lecture environment, or with the assistance of an instructor-produced video, outside of the lecture environment, and to store the results of this work side-by-side with instructional text.

Figure 1 depicts two pages of the ME 27400 Lecturebook which are representative of Lecturebook sections designed for factual content delivery and to introduce an example problem, respectively. As evident, the style of factual information delivery largely mirrors a traditional text, while the example problems are cast in terms of a *Given-Find* format. The latter is designed to bring clarity to the thought processes of novice students who are still establishing their baseline problem-solving skills. To exercise higher levels of cognition, the aforementioned content is augmented on both an intra- and inter-topic basis with *Challenge Questions* and *Conceptual Problems*. The *Challenge Questions* are specifically designed to have students expand their depth of knowledge by applying a recently-exercised concept to a fundamentally new system or by challenging widely-held, yet faulty, technical assumptions. In contrast, the *Conceptual Problems* require students to evaluate the applicability of a particular problem-solving strategy to an appropriately-scaled engineering example or to synthesize multiple pieces of technical information to solve a more-realistic technical problem, which is accompanied by an open-ended problem statement.

Complementing the printed Lecturebooks is the connective tissue of the PMFC experience: highly-interactive course blogs (see Figure 2). These blogs, hosted by university servers and currently based on the freely-accessible WordPress content management system, serve as repositories for course information and multimedia and, more importantly, venues for peer-to-peer and student-to-instructor virtual interaction. The repository functionality not only allows the students to rapidly access course syllabi, homework assignments, sample examinations, and multimedia content from a wide variety of electronic platforms on a twenty-four hour, seven days a week basis, but also provides instructors the same degree of flexibility in content delivery. Likewise, the discussion thread functionality allows the students and instructors to communicate asynchronously regarding administrative issues (e.g., grading policies, content corrections, or exam coverage), homework assignments, and other course deliverables. To help stimulate this this communication, the PMFC instructors regularly initiate discussion threads related to the specific problems that appear in homework assignments or on sample examinations. These threads contain key diagrams, brief problem descriptions, and/or technical hints. Apart from this initial stimulation, the discussion threads typically require little, or no, instructor intervention, as the students regularly and rapidly answer each other's questions and are quick to identify and correct technical errors. In this regard, the course blogs are true venues of peer-to-peer communication and instruction. As an added benefit, the blogs also provide a porthole through which instructors can anonymously observe their students and evaluate, in a holistic sense, their understanding, without the use of a more traditional evaluation mechanism, such as a homework assignment, quiz, or examination. This informal evaluation has proven very useful for tailored lecture preparation and within-semester instructional adaptation.



**Angular Acceleration of the Rotating Reference Frame**

By definition, the angular acceleration $\vec{\alpha}$ of the rotating reference frame is the time derivative of its angular velocity $\vec{\omega}$:

- For 2D problems, the moving reference frame is rotating about a FIXED axis that is perpendicular to the plane of motion; specifically, this rotation is about the fixed axis. For example, suppose that the angular velocity of the moving reference frame is given by: $\vec{\omega} = \Omega\hat{K}$. The angular acceleration of the moving reference frame is therefore given by:

  $$\vec{\alpha} = \frac{d\vec{\omega}}{dt} = \frac{d}{dt}\left(\Omega\hat{K}\right) = \frac{d\Omega}{dt}\hat{K} + \Omega\frac{d\hat{K}}{dt} = \dot{\Omega}\hat{K},$$

  since $\hat{K}$ is a FIXED axis.

- For 3D problems, the differentiation to find $\vec{\alpha}$ is not so simple. As we have discussed, $\vec{\omega}$ typically has rotation components about both fixed and moving axes. Consider the 3D system shown below where the U-shaped frame is rotating about the fixed $\hat{J}$ axis at a rate of $\omega_1$, and with the disk rotating about the moving $\hat{i}$ axis at a rate of $\omega_2$. This gives the total angular velocity of the disk of:

  $$\vec{\omega} = \omega_1\hat{J} + \omega_2\hat{i}$$



**Example 3.B.2**

**Given:** The radar antenna is rotating about a fixed vertical axis at a constant rate of $\Omega = 0.2$ rad/s. The angle $\theta$ is increasing at a constant rate of $\dot{\theta} = 0.5$ rad/s. The observer and the $xyz$ axes are attached to the antenna dish, with the $XYZ$ axes being fixed.

**Find:** Determine:
(a) The angular velocity of the observer when $\theta = 36.87°$; and
(b) The angular acceleration of the observer when $\theta = 36.87°$.



**Figure 1.** Two representative pages of the ME 27400: Basic Mechanics II Lecturebook[2]. As highlighted here, factual descriptions included in the Lecturebooks are complete, yet concise, while the examples are accompanied by ample white space, which is suitable for note taking.

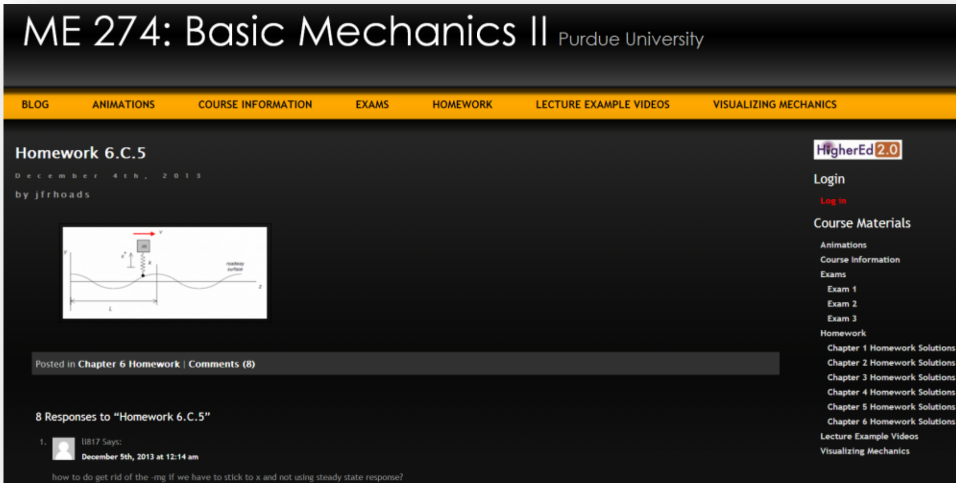



**Figure 2.** A screen capture of the course blog for the Fall 2013 Semester of ME 27400: Basic Mechanics II.

Though blog-enabled, peer-to-peer and student-to-instructor interactions lead to significant out-of-classroom learning, these features are buttressed in the PMFC by a wide array of multimedia content, designed specifically for self-paced delivery, and ultimately self-learning. The cornerstone of this multimedia content is the collection of hundreds of instructor-produced videos (Basic Mechanics II, for example, currently has more than 400 associated videos), which highlight, in a step-by-step fashion, the problem-solving approaches required for all of the course's lecture examples and homework problem (see Figure 3). These videos, recorded using tablet computers in conjunction with commercial recording software and hosted on YouTube, not only reinforce the material covered within lecture, leveraging the worked-example effect[3], but allow the students to rapidly access instructor expertise during homework completion and exam preparation. Additionally, due to the advanced nature of modern streaming video, the students can recall this expertise in a highly-tailored fashion, honing in on key conclusions, or the particular steps in a solution with which they are struggling.

Accompanying the above-referenced lecture example and homework solution videos is an ever-increasing number of videos in the PMFC's *Visualizing Mechanics* series. These instructor-conceived, student-produced videos leverage the power and popularity of YouTube by converting various lecture demonstrations and classroom experiments that are used to convey key mechanics concepts into internet-based videos. The intent here, as in the lecture example and homework videos described above, is to enable asynchronous recall and reinforcement, though in this case via visual and physical mechanisms. To this end, prior students of the PMFC are used to provide technical introductions and voice-overs of experiments which are either difficult to re-create in a classroom setting, due to equipment or safety restrictions, or benefit from the visualization capabilities (e.g., path tracing) attendant to modern filmmaking.

The most traditional component of the PMFC experience is the classroom lecture. Though lecture format and style can vary dramatically from instructor to instructor, the PMFC model encourages a strong emphasis on engineering fundamentals, highly-interactive and open-ended technical discussions, classroom demonstrations, and the inclusion of extended examples or case studies that parallel world events and/or technical situations that arise in the students' lives. Though the current lecture format utilized in the PMFC in part mimics a traditional format, it is worth noting that there has been considerable investigation of lecture inversion. For example, Basic Mechanics II previously utilized a flipped lecture format in a single section experiment, wherein the more traditional lecture components were pre-recorded and made accessible in conjunction with the multimedia content noted above, and class time was utilized for instructor-supervised collaborative learning exercises and daily quiz-based assessment. Though this approach offers significant pedagogical appeal, it received mixed feedback from the students and rendered no measurable difference in student outcomes. Accordingly, the more traditional lecture format continues to be utilized at the present time.

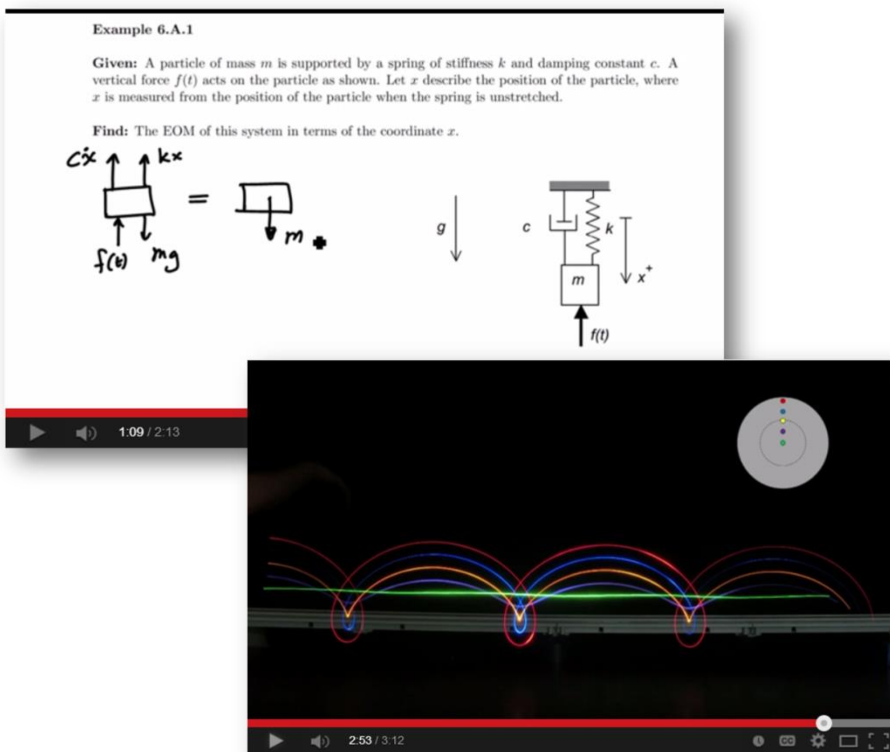



**Figure 3.** Screen captures of (upper left) a representative lecture example video and (lower right) a representative Visualizing Mechanics video. The latter depicts an experiment wherein the paths of motion of various points on a rolling spool are being traced.

The non-traditional nature of the PMFC predicates a need for adapted student evaluation. To this end, the traditional, homework-quiz-examination, problem-solving focused evaluation model long utilized in Basic Mechanics I and II has been replaced with a subtly-modified variant. In this refined evaluation model, homework assignments continue to be utilized as the principal practice ground for problem-solving skills. Unlike before, however, the newly-created problems are presented in the exact *Given-Find* format as the examples in the Lecturebook and the students are asked to follow a regimented problem-solving process. Given the strong encouragement for students to communicate and collaborate with one another via the course blogs, the emphasis in evaluation is placed on process over product, and final answers are deemphasized. Periodic in-class quizzes, previously used as a form of time-constrained problem-solving assessment, are currently used to evaluate conceptual understanding. To this end, students are frequently encouraged to work in groups on these assignments and tackle questions which involve higher levels of cognition. Finally, examinations are used to not only formally assess the problem-solving skills and conceptual understanding covered by the homework assignments and quizzes, but also to provide a venue for technical synthesis as realized via more complex engineering problems.

Apart from the core components highlighted above, there is also considerable ongoing experimentation within the PMFC with other pedagogy-driven instructional elements. These include:

- *Using the Index of Learning Styles (ILS)*[4-6] *to categorize learning style preferences and tailor information delivery.* The ILS is a relatively simple measure of how students prefer to receive information. The survey divides learning style preferences into four domains with opposing descriptors, visual-verbal, active-reflective, sensory-intuitive, and sequential-global. Using these domains, it has been established that students tend to prefer visual, active, and sensory modes, despite the fact that traditional lectures are predominantly reflective, intuitive, verbal, and sequential (i.e. nearly orthogonal in form to the preferred learning modes)[4-6]. To accommodate this, there have been concerted efforts made in experimental sections of Basic Mechanics I to include tailored active learning breaks and brief visualization exercises within the lecture environment.
- *Using everyday examples to improve student engagement.* Case studies have been shown to improve student engagement and learning, particularly in populations of female students[7-13]. In light of this, efforts have been made in Basic Mechanics I to introduce concepts that the students have already, often unknowingly, internalized and use them to illustrate specific technical concepts. Everyday examples utilized to date include technical scenarios arising in roller coasters, popular movies and sports.
- *Using thematic case-based instruction to enable the simultaneous teaching of technical and soft engineering skills.* Thematic Case-Based Instruction (TCBI) is an emerging technique designed to enable the simultaneous instruction of technical and so-called soft engineering skills through the coordinated application of international case studies[13]. Efforts have been made in Basic Mechanics I to utilize TCBI in such a way that students can not only assimilate technical information, but can also develop an appreciation for international engineering cultures; gain knowledge of, and sensitivity to, cultural norms; understand the differences in problem definitions and problem solving strategies that exist between cultures; and gain an appreciation for ethical responsibilities.

Before proceeding with an overview of assessment and a frank evaluation of the efficacy of the PMFC, it is important to note that few of the core and experimental components detailed above are truly original in form. Workbooks, blogs, instructional videos, case studies and concept-based evaluation tools, for example, all have been utilized, with varying degrees of success, in educational contexts[7-9,13-28]. As such, the true novelty of the PMFC largely stems from the simultaneous, near-seamless integration of these elements, its focus on introductory mechanics topics, and the scale of its reach (currently more than 1000 students per year).

## Assessment

Given the relative infancy of the PMFC, a complete and thorough assessment is yet to be completed. Despite this fact, there exists appreciable data related to content usage, student opinions, and macro-level success metrics (e.g. overall course grades), capable of providing key insights about the efficacy of the PMFC approach as applied in mechanics education. This section attempts to provide an assessment of this data, adopting a formal approach, where possible, and an anecdotal approach, where necessary. A complete and proper assessment is slated to commence in the summer of 2014.

One informal way to measure the efficacy of the PMFC is to examine student usage statistics. This tends to be especially insightful for instructors, as the use of most of the PMFC materials is not compulsory (Though in some sections of Basic Mechanics I and II a baseline level of blog participation has been incentivized at an inconsequential level.).

Lecturebook usage is perhaps best characterized through net sales, as the texts typically change on a semester-by-semester basis and are seldomly reused. Over the five semester history of ME 27000, and seven semester history of ME 27400, using the PMFC, approximately 90% of students have purchased the corresponding course Lecturebook, and, based on instructor observations, approximately 80% of these students regularly use the text for note taking as originally intended. Comments on student evaluations reveal that the source of these high adoption rates is two-fold: Many students speak positively of the texts' structure, stating "*The text is also very useful because notes are so easily taken in it.*" and "*I also like the textbook. It only has relevant information and practice problems.*" Others simply praise the fact that the retail costs of the Lecturebooks are a small fraction of their more traditional counterparts'.

Given the power of web-based analytical tools such as Google Analytics, electronic student usage statistics are relatively easy to assess. Given that these statistics, as well as the overall efficacy, of blog usage in mechanics education have been investigated in prior literature by the authors, a complete review has been omitted here for the sake of brevity[14,15]. Worthy of repeating is the fact that, prior to the complete implementation of the PMFC, approximately 70% of students visited the course blog at least once a week and about 75% of students actively participated in online discussions about the course material. Since the initiation of the PMFC, instructor-initiated discussion threads, created at a pace of approximately six per week, typically receive 10-30 comments from students in smaller classes (those of ~100 students) and often more than 50 comments per day from students in larger classes (those of more than ~300 students). Student evaluations are also quite supportive of the course blog, and frequently echo the sentiment that *"The blog is a huge help and I highly recommend continuing with it. It helps to learn from and helps other students apply their knowledge to help explain to others [sic]."*

While the communication-oriented usage statistics for the course blogs noted above provide impetus for their sustained use, perhaps more interesting are the usage statistics related to the blogs' repository (or, more accurately in this case, linking) functionality. Figure 4, in conjunction with Tables 1-3, highlights these statistics for a recent section (Fall 2013) of Basic Mechanics II, which had 138 enrolled students. As these statistics reveal, the average student in this section utilized the blog to watch 258 minutes of instructor- or student-produced online videos – the equivalent of 5.16 class periods! As evident from Figure 4, this student viewership was strongly tied to exam preparation, which is expected given the videos' recall and reinforce functionality, and weakly tied to homework submission. In addition, and as expected, students rarely watch a complete video, choosing instead to focus on those segments of the movie which addressed gaps in their own technical understanding. Interestingly, but perhaps not surprisingly, students appear to favor the *Visualizing Mechanics* videos, which, as noted above, utilize experimental demonstrations to buttress in-class learning, as well as the homework solution videos, though viewership of the lecture example videos was far from inconsequential.

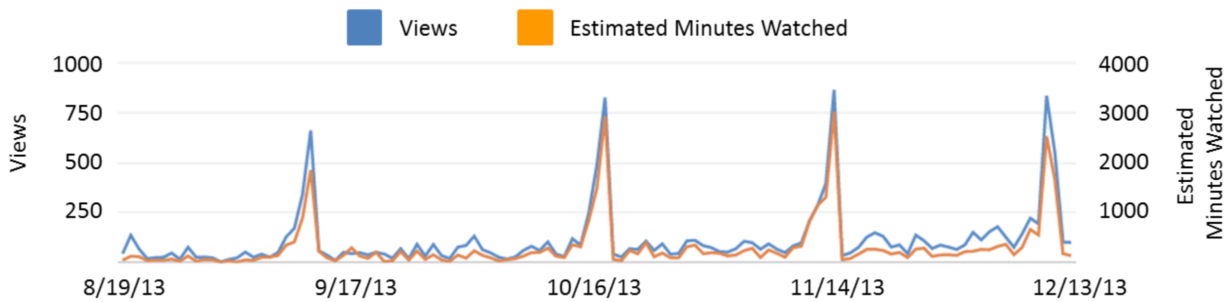



**Figure 4.** Longitudinal study of video viewership acquired from the Fall 2013 Semester of ME 27400: Basic Mechanics II. These metrics were obtained using YouTube's analytics engine. Note that the four peaks in viewership occur in the proximity of the course's three midterm and final exams.

**Table 1.** Video summary metrics acquired from the Fall 2013 Semester of ME 27400: Basic Mechanics II. These metrics were obtained using YouTube's analytics engine.

| Summary Metric | Result (8/19/13 – 12/13/13) |
|---|---|
| Total Number of Videos (lecture example videos, homework solution videos for assigned problems, and *Visualizing Mechanics* videos) | 270 |
| Total Video Views | 13,204 |
| Estimated Minutes of Video Watched | 35,629 minutes |
| Estimated Minutes of Video Watched Per Enrolled Student (approximate) | 258.2 minutes/student (5.16 equivalent class periods) |
| Average Viewing Duration | 2:41 |
| Average Percentage of Video Viewed | 39% |
| Predicted Demographics (from logged-in viewers; note that the class was made up of 20.5% female and 79.5% male students) | 85% Male<br>15% Female |
| Device Type | 89% Computer<br>7.4% Tablet<br>3.6% Mobile Phone<br>0.3% Other |

**Table 2.** Video breakdown from the Fall 2013 Semester of ME 27400: Basic Mechanics II. These metrics were obtained using YouTube's analytics engine.

| Video Category | Total Number of Videos | Percent in Top 200 |
|---|---|---|
| Lecture Example | 168 (62.22%) | 66.07% |
| Homework Solution | 85 (31.48%) | 90.59% |
| Visualizing Mechanics | 17 (6.30%) | 70.59% |

**Table 3.** Top ten videos (as measured by the number of views) from the Fall 2013 Semester of ME 27400: Basic Mechanics II. These metrics were obtained using YouTube's analytics engine.

| Video | Number of Views | Estimated Minutes Watched | Average Percentage Viewed |
|---|---|---|---|
| Visualizing Mechanics: Radius of Gyration | 979 | 2,042 | 49.07% |
| Visualizing Mechanics: Natural Frequency of a Spring-Mass System | 379 | 377 | 70.21% |
| Visualizing Mechanics: Instantaneous Centers of Rotation | 250 | 454 | 41.89% |
| Visualizing Mechanics: Rotating Reference Frames – Merry-Go-Round | 168 | 297 | 54.45% |
| Homework Solution 1.A.1 | 144 | 310 | 42.32% |
| Homework Solution 1.A.2 | 116 | 377 | 60.60% |
| Homework Solution 5.A.1 | 90 | 237 | 59.13% |
| Homework Solution 5.A.2 | 88 | 301 | 57.72% |
| Homework Solution 1.C.2 | 85 | 275 | 49.54% |
| Homework Solution 1.C.1 | 85 | 237 | 46.30% |

One natural question which stems from the statistics summarized in Figure 4 and Tables 1-3 is related to the impact that having extensive online content has on attendance and in-class participation. Though not formally studied to date, anecdotally speaking typical lecture attendance appears to have actually increased with the implementation of the PMFC (to approximately 85-95%, compared to ~70%). Interestingly, instructors commonly report that the quality of in-class discussions and student engagement has increased as well.

Though the usage statistics and student comments included above cast a positive light on the PMFC and its constituent components, an alternate and perhaps more instructive way of assessing the efficacy of instruction is to examine the distribution of grades earned by students in each of the mechanics classes involved in this transformation. Figures 5 and 6 present the percentage of students earning A, B, C, D, and F grades, or a W marking (resulting from a withdrawal from the course before completion) in the Basic Mechanics I and II courses since the Fall 2008 (Spring 2009 in the case of Basic Mechanics II) Semester, which is prior to the complete implementation of the PMFC. Data is presented for fall semesters (spring semesters in the case of Basic Mechanics II) only, as this is the typical semester during which the most students are enrolled in this course. Note that D, F and W markings are aggregated here, as each of these grades indicates an unsuccessful attempt at mastering the course material. In addition, students who earn a D, and F, or withdraw from the course prior to completion have a higher risk of extending their undergraduate education beyond eight semesters and have a higher rate of attrition. Figures 5 and 6 highlight the fact that the DFW rates of the courses have been substantially lowered since the implementation of the PMFC. For example, the DFW rate in Basic Mechanics I was 32% in the fall semester of 2008 and was most recently 18% in the fall semester of 2013. Likewise, the DFW rate in Basic Mechanics II was 21% in the spring semester of 2009 and was most recently 11% in the spring semester of 2013. Interestingly, though the median course grades have generally increased, this increase, and the corresponding decrease in DFW rates, are not believed to be tied to traditional grade inflation mechanisms, as the instructors believe the course content is actually more difficult within PMFC than it was prior to its implementation.

As a point of reference, it may be helpful to compare the PMFC-related grade distributions to another introductory mechanical engineering class, which did not incorporate these same pedagogical changes. To this end, Figure 7 presents the percentage of students earning A, B, C, D, and F grades, or a W marking, in the introductory thermodynamics course ME 20000: Thermodynamics I. Data is presented for fall semesters only, as this is the typical semester during which the most students are enrolled in this course. Figure 7 shows that the DFW rate of the course hasn't followed the same downward trends as can be seen in Basic Mechanics I and II. Interestingly, in the fall semester of 2013, formal supplemental instruction was added as an option for students in the course; potentially contributing to the significant decline in the DFW rate from fall semester of 2012 (44%) to the fall semester of 2013 (22%). It is also interesting to note that the lowest DFW rate for Thermodynamics I (22% in the fall semester of 2013) is greater than the highest DFW rate seen in Basic Mechanics II (in the spring semester of 2009) and higher than the DFW rates seen in the three most recent semesters of Basic Mechanics I.

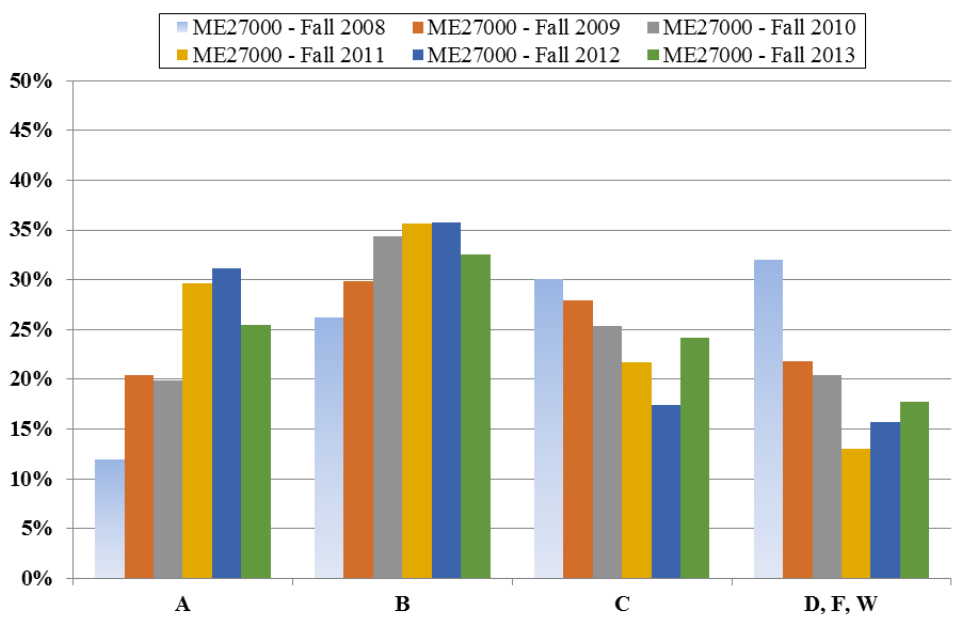



**Figure 5.** Grade distribution for ME 27000: Basic Mechanics I in the fall semesters between 2008 and 2013.

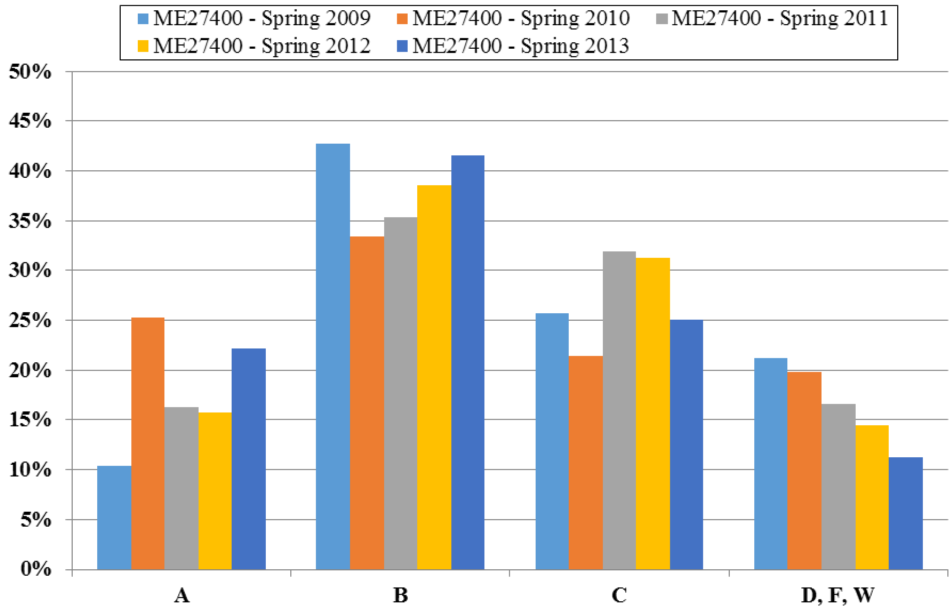



**Figure 6.** Grade distribution for ME 27400: Basic Mechanics II in the spring semesters between 2009 and 2013.

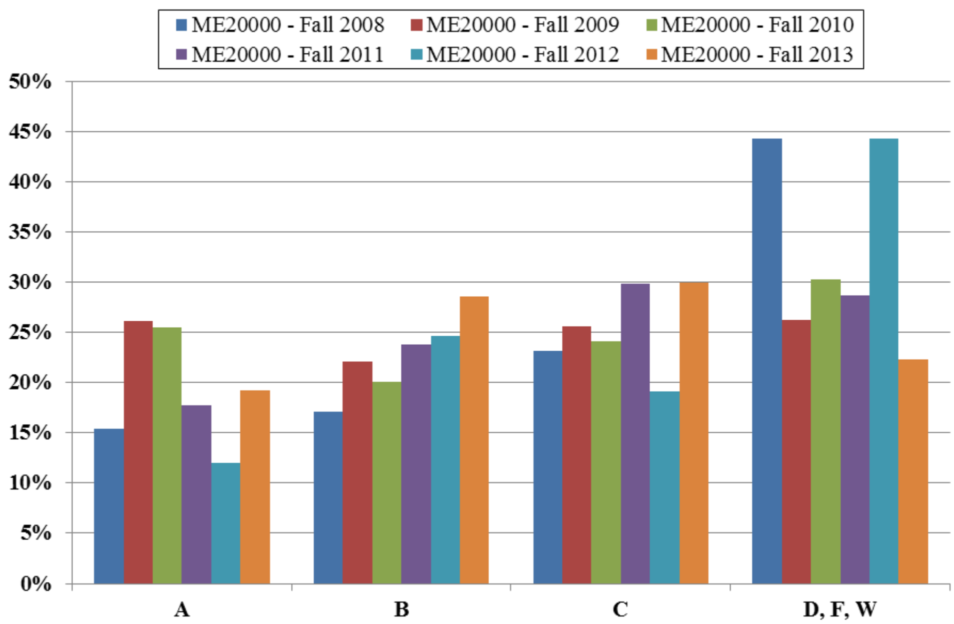



**Figure 7.** Grade distribution for ME 20000: Thermodynamics I in the fall semesters between 2008 and 2013.

## Faculty Adoption

Despite the seemingly positive impact of the PMFC on student performance and outcomes, there remain key challenges for broader implementation, most of which are strongly tied to faculty buy-in. In many ways, the authors have observed that other faculty members, particularly those that are technology adverse, are the rate-limiting process in curricular reform. Experience indicates that there are four interventions that can be utilized to successfully implement new teaching methodologies akin to those described here. First, as much as possible of what the other instructors are currently doing should be integrated into a new delivery tool. In the case of the PMFC, this required adapting the various instructors' examples and preferences into the Lecturebook and online materials. Second, a continuous quality improvement framework, inclusive of overall student performance and updated on a semester-to-semester basis, should be required for all courses to encourage the adoption of demonstrably successful methodologies by individual faculty members. Third, administrative support for the faculty must be provided in order to create a system of rewards for those faculty members that participate in curricular development activities. Finally, attempts should be made to lower the overhead associated with content creation and maintenance for new course instructors.

## Conclusions and Future Growth

In summary, the Purdue Mechanics Freeform Classroom represents a new approach to mechanics education, which leverages elements of the traditional classroom in conjunction with new Lecturebooks, course blogs, extensive multimedia content, and refined evaluation mechanisms. This unique combination of tools leads to significant student engagement, both inside and outside of the lecture environment, and appears to improve many students' technical competency, as well.

Currently, efforts are being made to formally access the efficacy of the PMFC and increase its breadth. On the latter front, ongoing efforts are specifically aimed at adding student-controlled interactive simulations based upon the Working Model simulation package; developing so-called Practical Knowledge Assessments (PKAs) – conceptual analogs of traditional real-world case studies; and developing electronic versions of the Lecturebooks, which are both amenable to electronic note taking and capable of directly integrating the PMFC's electronic content. With this continued development and expansion the authors hope that the Purdue Mechanics Freeform Classroom can be adopted at colleges and universities across the globe, rendering a positive and uniform mechanics education experience for all.

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