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Changing the Static: Insights and Early Results of a Shift toward a Studio-Style Statics Class

Dr. Christopher Papadopoulos, University of Puerto Rico, Mayaguez

Christopher Papadopoulos is Professor in the Department of Engineering Sciences and Materials at the University of Puerto Rico, Mayaguez Campus (UPRM).

Changing the Static: Insights and Early Results of a Shift to a Cooperative Learning Format in Statics

In this paper I will provide a first-person account of the evolution of my approach to teaching Statics, culminating in a recent fundamental change (Fall 2022) to teach statics in a "Studio format" characterized by cooperative and experiential learning. My account will provide both qualitative and quantitative data to indicate that the Studio format is effective and worthy of continued use and refinement.

1. Background Narrative.

My first era of teaching, starting midway through my graduate studies in Theoretical and Applied Mechanics (T&AM) at Cornell University in 1997-2000, and continuing from 2001-08 in the Department of Civil Engineering and Mechanics at the University of Wisconsin-Milwaukee, was characterized primarily by direct lecturing in front of a board. Indeed, with little formal training, my teaching modeled how I was taught (Felder & Brent, 2016). I attempted to engage students following my intuition, with such active elements as asking frequent questions, guided activities in recitations led by TA's, student presentations, and a few attempts to link the course material with social context or current events. Of note, motivated by my freshman Physics professor and noted educator Hugh D. Young at Carnegie Mellon who told us during our first week that "the office hours are perhaps the most underutilized resource at the University", and later facilitated by the culture in the T&AM Department, as teaching assistant and novice lecturer I held office hours in the Harry "Don" Conway Mechanics Study Room, so as to encourage active inquiry with as many students as possible. To this day, I continue to hold office hours in a classroom or other collaborative space. But on the whole, my mentality was "to cover the material" and "to show the students how to get the right answer", with the students' twin mentality "to get the right answer."

In 2009, after moving to the University of Puerto Rico, Mayagüez, I made a fundamental change to use the inverted classroom format, after hearing several presentations about this topic at that summer's ASEE meeting. I developed a comprehensive set of PowerPoint lectures, complete with dynamic text and animations to help students better see the development of the ideas (or so I thought). Despite my initial hesitation, I quickly became accustomed to not reciting notes at the board or from PPT. Typically, I would establish a weekly problem set of traditional textbook problems, lead an opening discussion of how to approach them, and then allow students time to work on them in class, with opportunity to consult directly with me, a peer tutor, or with a fellow student. I aimed that students would 'crack the egg' of the fundamental ideas during these working periods, and then complete them for homework. Nevertheless, I still had the mentality "to cover the material" and "to show students how". Thus, lectures would tend to migrate back to me serving as the central figure leading a class discussion on how to outline problem solutions. True, I was not reciting lecture notes, and using a Socratic style, I would not show any explicit steps unless a student provided it. I also took care to invite ideas for alternative solution pathways. But this dynamic tended to allow students who were less willing or able to keep up to silently watch or disengage (indeed, grade distributions were typically bi-modal, dividing the students who 'kept up' from those who did not). Early evidence of effectiveness, based on summative results from the Concept Assessment Test for Statics (CATS), were modest (Papadopoulos & Santiago-Román, 2010).

As I continued to use the CATS, I began integrating concept-based instruction, and was delighted to engage the Concept Warehouse. A primary motivation was to have a large bank of questions that could be discussed freely in class without risking the integrity of the Inventory as an assessment instrument. The platform now has a bank of about 300 concept questions for Statics and is very effective to elicit student written responses, drive conversation, and peer more deeply into student reasoning (Papadopoulos et al., 2022). However, even though there is a high rate of student response, the corresponding grade weight was no more than 5% of the grade. In this context, I have not yet established firm evidence that experience with concept questions improves performance on procedural test questions, although this has been previously argued (Koretsky et al., 2016)

During the last decade or so, I have also begun to "contextualize" problems in both homework and exam settings to address issues of ethics, social justice and sustainability (Leydens & Lucena, 2017), (Papadopoulos & Nettleship, 2020). Corresponding activities, however, were typically not weighted as 20% or less of the grade, and although I received a number of thoughtful essays, these activities did not directly translate into tangible gains of performance or engagement. Yet, without being fully conscious of it, these forays helped me begin my gradual shift of mentality from "showing how" to "coaching through".

In 2020, I attended a workshop on Mastery Based Learning (MBL) at the virtual ASEE Conference led by Sara Atwood and Kurt DeGoede of Elizabethtown College. MBL is characterized by students earning grades through 'mastering' discrete competencies based on targeted short tests on specific topics, rather than earning grades based on average test scores with partial credit. In my implementation, the course topics were grouped into categories corresponding to grade levels D, C, B, and A. Each category has 3-5 topics [D1-D5, C1-C4, B1-B3, and A1-A3], and the corresponding grade is earned if a short test for each topic (or in some cases, a pair of topics) in the category is "Approved". A grade of Approved is earned for demonstrating A-quality work (only minor errors permitted). A grade of "Conditionally Approved" is earned for demonstrating B-quality work, with full approval being earned through writing corrections. A grade of "Not Yet Approved" is assigned for demonstrating C or lower quality work, with full approval requiring another test of the same topic to be taken. In order to facilitate this, and in keeping with the philosophy of learning through revision and correction, opportunities to retake tests were given weekly, with nearly no restrictions on the number of attempts permitted beyond the calendar ending of the semester.

I had, and continue to have, mixed feelings about MBL. Breaking the topics into small pieces appears to dissolve the 'beautiful complexity' of problems that combine several ideas. Does this diminish what I am teaching, and does this encourage students to simply 'learn for the test'? On the other hand, I like the idea of students learning from mistakes – perhaps better framed as continuous refinement of concepts – and I convinced myself (and another colleague) that MBL would engage students by giving them tangible goals and incentive to incrementally master topics through a structured cycle of learning, trying, rethinking, and trying again – to some degree at their own rate. In this process, I also gained some valuable new insights into how students think about Statics, which I will leave for the subject of a future article. Briefly, however, it illustrated that the fundamental issues with learning Statics are not only about the 'mechanics' concepts, but critically rest on the ability to confidently and creatively apply basic skills of algebra, geometry, trigonometry, and sketching.

My two-year experience using Mastery Based instruction, and the corresponding student results and experiences, were no doubt colored by the conditions of the pandemic. Still, what emerged was that students did not seem to take sufficient advantage of the multiple test opportunities to learn from their errors, as evidenced by the fact that many students committed the same errors repeatedly over three or more tests on the same topic (Papadopoulos et al., 2021). I also began to reflect on the fact that although there was something cyclic about the process, it was still dominated by abstraction, and missed the 'concrete' aspects suggested by Kolb (Mahmoud & Nagy, 2009).

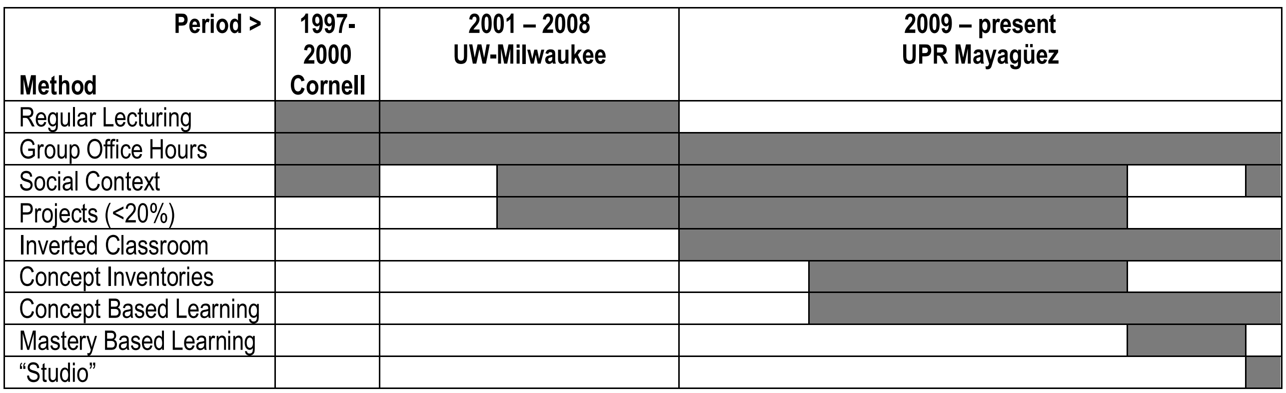
Throughout this trajectory, with few exceptions, generally 45%–55% of students earned the grade of A, B, or C. I began to consider that none of the approaches appeared to adequately engage the majority of students. Inverted classroom teaching has the caveat that students who do not keep up with the reading or video lessons, fall behind and do not volunteer questions or responses in class. Concept-based instruction does close that gap to some extent, but even with the opportunity to write explanations – which can help students to be confident to speak in class – many still do not volunteer to voice what they have written. With MBL instruction, the opportunity to retest did not drive as many students to office hours or for self-driven deep inquiry to the degree that I had hoped.

One day as I was sharing some of this with a colleague, who then asked, "is it possible to teach Statics without giving tests?" Caught off guard, a mixture of dismissiveness, intrigue, and even fear crossed my mind. But I could not put the question away. Plus, in the first semester returning to in-person classes after the pandemic, I happened to have had an artistically inclined student who I observed to make excellent progress on fundamentals, largely due to their use of large paper and sketching. The idea was hatched: I decided to one more time overhaul the class, this time in a "studio-style" format, characterized by (1) maintained use of inverted classroom to expect reading or watching content prior to class; (2) abstraction balanced with concrete experiential and exploratory activities measurement, sketching, photographing, physical models, observation, and seeking; (3) implementation of cooperative learning with the vast majority of class-time devoted to working on activities in teams, with instructors and tutors providing coaching and consultation; and (4) balanced grade weighting so that 50% is based on the team activities, and 50% is based on individual tests.

Thus, I retained testing, but for the first time ever in my career, a significant portion of the grade rewarded activities other than tests, and other than analytical abstraction. Tasks such as sketching, measuring, observing, and explaining can be completed by following relatively simple directions, often providing a ‘safe’ environment to encourage activity. Results that are not ‘correct’ are not severely penalized if well documented and explained, and in fact, are often used for starting deeper discussions. Also, the team-based structure shifts student accountability to be to the other teammates, and not only to the instructor. I believed that this new format would lead to tangible learning gains, and so far, with one semester completed plus the current semester in progress, I am encouraged that this is the case. As will be discussed in Section 3, test performance, as compared with that of the MBL cohorts, has generally improved, and the percentage of students earning at least C has increased.

Before proceeding, I present a summary of the various methods that I have employed over three phases in my career in Table 1.

Table 1: Approximate Chronogram of Teaching Methods Employed.



2. The Statics Studio: Cooperative and Experiential Learning Environment

The primary definition of “studio” in the Meriam Webster Dictionary is “(1a) the working place of a painter, sculptor, or photographer; (1b) a place for the study of an art (such as dancing, singing, or acting)”. This definition evokes a place to be active, creative, and productive, and it suggests the environment that I seek to establish in the class going forward.

To put this into context of Engineering pedagogy, the studio is essentially a combination of Cooperative/Team-based Learning and Experiential Learning: cooperative in that students are assigned teams for their activities, and experiential in the sense that activities are not simply written analytical homework problems, but require concrete actions such as drafting to scale, measurement, small model building, observation, explanation, and interpretation. Inverted instruction continues to serve as the base for the Studio format, because students still must complete a reading or video summary of the background material prior to class. The difference, however, is that whereas in the past I would provide time in class for students to work on homework-type problems individually or in informal pairs at their desks, in the new Studio format, the class is essentially devoted for team problem solving with students facing each other at tables, with little preamble.

To elaborate, typically 80% or more of the class is spent working on the activities, though it is expected that students will work in their teams outside of class for a few hours per week to complete them. During class, I primarily play the role of mentor, and I also employ a skilled undergraduate peer tutor to provide further consultation opportunities. In past instances of my use of the inverted classroom, many students could still 'opt out' or 'hide' by choosing not to ask or answer questions. Now, in the Studio format, I have a direct face-to-face conversation with each team two or three times per class. This interaction builds trust, accountability, and generally good communication.

The activities are no longer traditional homework problems, but incorporate a balance of analytical and concrete tasks. The analytical tasks include the usual trigonometric analysis, free body diagrams, and equilibrium equations; the concrete tasks include those cited as the "experiential" elements in the preceding paragraphs. In developing the activities, I borrowed ideas from (Davishahl et al., 2020) and (Barrage et al., 2017), and made use of commonly available tools and materials, such large grid paper, rulers, protractors, spring scales, wrenches, pliers, clothespins, Legos, and cell-phone/tablet cameras. The activities consist of a set of written questions, without figures, to promote the skill to interpret important details and drive students to create the visual interpretations. The Appendix provides the details of the activities. Figure 1 illustrates some typical scenes from the Studio class format.

Figure 1. Scenes from the Studio Class. Clockwise from upper left: Studying the equilibrium of a ring, measuring forces and angles; measuring the angles on cables supporting a water bottle; Lego models; using Lego models to understand reactions in Free Body Diagrams.

Table 2 provides a summary of the key characteristics of the primary teaching methods that I have employed, illustrating the distinguishing features of the Studio format. I note that the Studio format continues to retain significant elements of prior methods, particularly the Inverted Classroom format at the use of the Mastery Tests (but not the repeated opportunities).

Table 2. Characteristics of Teaching Methods

Phase > Element	Regular 1997-2008	Inverted F2009-present	Inverted + Mastery F2020-S2022	Inverted + Studio F2022-present
Lecture Format/ Instructor Role	Instructor presents notes on board and leads Q&A with entire class	Minimal notes presented; Q&A with entire class; example-driven; Instructor provides some individual consultation; minimal role for tutor		Minimal notes presented; activity-driven; Instructor and peer tutor provide continuous individual and team consultation/mentoring.
Learning Environment	Individual Learning			Cooperative/Team Learning Experiential Learning
Accountability	Students are accountable only to the instructor.			Students are accountable to teammates and to the instructor.
Style of Activities	Abstract analysis, pencil & paper			Abstract and Concrete: mixture of pencil & paper with measurement and calculation
Seating	Front-facing individual desks			Tables, mixed orientation
Tests	2 comprehensive tests per semester, up to 50% points lost can be recovered with corrections		Weekly opportunities for short tests, frequent retaking	4 short tests per semester, using combinations of mastery tests; periodic retaking
Grading	Average grading with partial credit; projects weighted < 20% of grade		Discrete approval, no partial credit; tests constitute 100% of grade	Average grading with partial credit; Activities = 50% of grade

As a final note before proceeding, in preparing the team aspect of the Studio format, I used (for the first time) the CATME system (https://catme.org). My primary use was to use the Team Maker Survey function to create teams that had compatible time schedules outside of class, reasonable range of student ability based on self-reported GPA, and non-isolation of underrepresented students. I am still learning to use the CATME effectively, and my use of its peer evaluation function is still in its infancy. Therefore I will not provide a detailed discussion of the use of the CATME system here.

3. Results

The organization of topics for the Studio format is nearly identical to that of the prior MBL format, as summarized in Table 3. However, in the Studio format, grades can be earned by averaging results, without requiring discrete minimum performance on specific topics.

Table 3: Topics Defined for Mastery and Studio Formats

D Group	C Group	B Group	A Group
D1: Vector Resultants D2: FBDs of Single Bodies D3: Particle Equilibrium D4: Moment Calculations D5: Rigid Body Equilibrium	C1: FBDs of Multiple Bodies C2: Trusses/Joints C3: Trusses/Sections C4: Frames and Machines	B1: Beams (Internal reactions and distributed loads) B2: 2D Centroids B3: 2D Area Moment of Inertia	A1: Friction A2: 3D Vector Operations A3: 3D Rigid Body Equilibrium
Notes. In MBL, each topic within in each group and each prior was required to be Approved in order to earn the corresponding grade, e.g., earning a C would require approval of D1-D5 and C1-C4 topics. For the Studio format, the topics remained with the same order and nomenclature, but grading was averaged, without the requirement to earn an approval for any given topic.			

Further, in the Studio format, the tests consist of two or three of the same Mastery Test questions. Therefore, a direct comparison of test results can be performed, with the following calibration:

- In MBL, test scores were "Approved", "Conditionally Approved", or "Not Yet Approved".
- In the Studio format, each test is scored from 0-4, with 3.00-3.50 corresponding to "Conditionally Approved", and 3.75-4.00 corresponding to "Approved". Scores below 3.00 represent a finer scoring that was not previously done in MBL.

Note that the grade determination is different: in the Mastery approach, each topic must be approved (mastered) in a grade category to earn the corresponding grade, e.g., each of D1, D2, D3, D4, and D5 would need to be approved; in the Studio format, although the same nomenclature is used, grades are averaged and assigned such that a D corresponds to an average of 1.00, C an average of 2.00, B, and average of at least 2.80, and A an average of at least 3.60.

Table 4 provides the historical cumulative results for the first attempts on the D Level and C Level Mastery Tests for all Mastery cohorts (F2020, S2021, F2021, S2022) and Studio cohorts (F2022, S2023), and Figure 2 provides a corresponding bar chart. The first attempt is considered to be the best metric for comparison given that the Studio cohort students typically take each test only once.

Table 4. Cumulative Mastery Test Results: Number and Rate of Students Earning at least Conditional Approval or Equivalent on First Attempt.

	D1		**D2**		**D3**		**D4**		**D5**		**C1**		**C2/C3**		**C4**		**B1**	
	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S
#A	82	48	51	31	63	27	42	31	39	20	32	31	65	30	21	17	27	11
N	246	90	243	88	224	87	208	87	187	87	192	86	262	89	122	85	92	42
%	33.3	53.3	21.0	35.2	28.1	31.0	20.2	35.6	20.9	23.0	16.7	36.0	24.8	33.7	17.2	20.0	29.3	26.2

Notes: #A = raw number of tests scored with Approved or Conditionally Approved in all Mastery Cohorts (F2020, S2021, F2021, S2022), or equivalently, a score of at least 3.00 in all Studio Cohorts (F2022, S2023), to date. N = total number of tests administered in the respective cohorts. % = #A/N. M = Mastery Cohorts; S = Studio Cohorts.

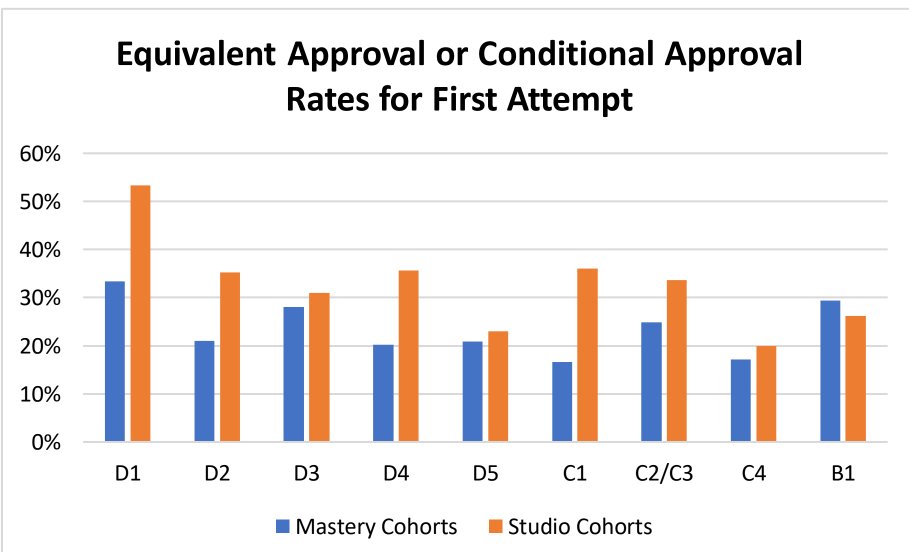


Figure 2. Bar Chart of Mastery Test Results Corresponding to Table 4.

Due to the small sample size of the Studio cohort (only one complete semester), no further statistical analysis has been conducted. Nevertheless, students in the Studio cohort consistently perform at or above the level of the students in the Mastery cohorts; the improvement is especially pronounced on the D1, D2, D4, and C1 tests, which are 'single fundamental skill tests', e.g., how to add vectors or how to draw reactions and free body diagrams. On the 'higher level composite tests', where multiple skills are combined, e.g., how to solve a truss or frame problem, the performance is similar for both cohorts.

Table 5 provides the historical rate at which students earn at least a C in my Statics classes at my current institution (%ABC). As was noted earlier, typically this rate is about 45% - 55%. As is seen, in Fall 2022, the first semester of the Studio format, 65% of students earned A, B, or C, which is the fifth highest ranking of the 24 semesters recorded.

Table 5. Number and Rate of Students Earning at least C in Statics.

Semester	Format	N	ABC
Fall 2009	Inverted	63	46 (0.73)
Spring 2010	Inverted	46	24 (0.52)
Fall 2010	Inverted	37	27 (0.73)
Spring 2011	Inverted	31	24 (0.77)
Fall 2011	Inverted	51	27 (0.54)
Spring 2012	Inverted	77	35 (0.45)
Fall 2012	Inverted	94	41 (0.44)
Spring 2013	Inverted	48	23 (0.49)
Fall 2013	Inverted	34	17 (0.50)
Spring 2014	Inverted	24	13 (0.55)
Fall 2014	Inverted	77	31 (0.40)
Spring 2015	Inverted	47	21 (0.45)
Fall 2015	Inverted	77	31 (0.40)
Spring 2016	Inverted	52	28 (0.53)
Fall 2016	Inverted	41	24 (0.59)
Spring 2017	Inverted	49	24 (0.49)
Fall 2017	Inverted	42	26 (0.61)
Spring 2018	Inverted	29	13 (0.45)
Spring 2020	Inverted	35	25 (0.72)
Fall 2020	Mastery	49	22 (0.45)
Spring 2021	Mastery	58	11 (0.19)
Fall 2021	Mastery	100	32 (0.32)
Spring 2022	Mastery	47	14 (0.30)
Fall 2022	Studio	48	31 (0.65)
N = total initial enrollment. The column ABC reports the number (and percent) of students earning A, B, or C.			

Table 6 provides selected student comments that illustrate a range of comments, classified as classified as "positive", "mixed", or "negative". These comments were collected as part of routine course evaluations.

Table 6. Student Comments.

Type	Comment
Positive	This class has been one of my favorites. The professor, my teammates, officer hours, the activities, I will always remember this class. It was the first engineering class where I actually felt like an engineer! Since this point on, I will make sure to always think twice if I'm in the right track, because this class certainly makes you do that. [B] It's a great class, this method works amazing and helps the team understand concepts by using real life examples. It's great for visualization and helps with understanding how the class will help us in the future when we are adults working in the industry. [C] Thanks for making this class an interesting one. I loved my teammates and wish them the best of the best. I won't forget everything that has happened. I thought I wasn't going to be okay after [a difficult personal experience], and [named teammates] made sure to always keep a smile on my face. I love them. [C]
Mixed	I really enjoyed the way you have given this class this semester and I appreciate you have had with me. My only complaint regarding the class was that I wished we would have a normal class at least once a week; maybe we could have like a normal class on Tuesday where you would re-review the material just to make sure everyone understood the entire lesson the way you do wanted and then the regular activities that we have every class day could have been done on Thursday and we could come review them on office hours just like we have been doing. Otherwise your class is lots of fun and a super interesting topic. [D] In terms of my classmates, I blame myself for not including them fully but also I can't be their teacher every time we step into a new problem. [B] This was a good dynamic, working with the activities helped understand the concepts but sometimes they were a little too long and took way too much time. [A]
Negative	It is very ineffective when it comes to learning the concepts. Not to say that the activities are bad, but instead that an initial explanation in class before starting the activities would be better for the understanding of the material in class. In other words, the reverse classroom feels counter-productive since when I review the material from the modules it feels hard to connect the material to what is being asked to do in the classroom. That might be in part because the way I effectively learn is through the classroom, but it might also be in part of having to juggle the online material with the material given in class. On a similar note, observing the dynamic during office hours, students (including myself) seem to enjoy that way of teaching to the one established in classroom. Further, it might be the time crush but the students also seem more focused on applying the concepts learned and are eager to understand the exercises that are being discussed. [B]
Notes: Comments have been lightly edited for clarity and to protect identity. The student's grade is reported in [brackets] following the comment.	

4. Discussion and Reflection

The limited data and experience with the Studio format are insufficient to make any reliable generalizations. However, the early results are very encouraging. Even with this short experience, it is clear that the test performance in the Studio cohort is frequently at or above that of the Mastery cohorts, and I speculate that this would generalize to the prior cohorts were I to establish a basis for comparison. Moreover, beyond test performance, the nature of the Studio format gives a large 'value added', in that it engages students with additional concrete activities that complement the usual abstractions of a conventional Statics class. In fact, I hypothesize that it is precisely these complementary experiences that feedback to improve performance in the 'core' test activities. Perhaps tasks so seemingly mundane as to measure angles and lengths of vectors on graph paper draw students in with a 'safe' task, build confidence with the abstract calculations, leading to more interest and engagement with the core topics. Perhaps 'feeling' how a reaction works with a Lego model or clothespin improves the ability to draw a Free Body Diagram.

Further, it is striking that students commented with some frequency that 'I felt like an engineer' and that they experienced 'love' from their teammates. I do not remember encountering those sorts of comments in my prior approaches, yet I argue that these expressions that exceed the content limits of the course are vital for the preparation of an engineer.

It is interesting that some of the most critical comments came from high performing students, but I take this seriously. Regarding the investment of time, the calibration of the Studio activities with the scheduled topics is not trivial, and in the current semester I am streamlining and/or providing additional guidance to help students complete the activities in a timelier fashion. I also acknowledge that last semester, I did not cover some topics due to falling behind as the semester went on, but a better adherence to schedule is occurring this semester.

Some students did express discomfort with the team dynamic and the inverted classroom method, and it is further interesting that some of these comments came from top performers. I do not discount this, and I am learning how to use CATME more effectively to address team conflicts. It is not unusual for some students to react negatively when they feel that they are asked to take a level of responsibility that has not previously been required, or when they feel they are doing more than their share of the teamwork (Felder & Brent, 2016). Ironically, perhaps students felt emboldened to comment on these aspects because I took time to explain my philosophy and to invite comments. Along these lines, in an office hours at the end of last semester, which turned into an impromptu focus group, some students had the courage to tell me that they liked the online textbook more than my own power point presentations. Listening carefully to these comments, this semester I now emphasize the textbook more than in the past.

Regarding the final grade distribution, I acknowledge that there is some potential artificiality with the improvement in the ABC%. The activities are graded as a team and consist largely of tasks that can be completed simply by following directions. Moreover, 'wrong' answers are often positively graded when inconsistencies are identified and explained. So, it is not surprising that weighing these activities at 50% of the grade is likely to increase the overall grade. However, this grade weighting buys engagement on a scale that I have not achieved before, and also rewards other kinds of learning and metacognition that enhance the context of the core content. Sure, some students still arrive unprepared and do not adequately participate (in which case a penalty or direct failure can occur), but on the whole, no one can hide from me, the tutors, or their teammates, and this level of engagement drives attention to task, which appears to drive improved performance. All of this is to say that the new grade weighting is merited.

As a final reflection, I find the class is more enjoyable to conduct, I feel that I am getting to know the students much better, and I can do deeper grading but in less total quantity. Rather than grading 100's of test questions per week, I grade about a dozen activities, plus a more reasonable amount of test questions. I can directly observe behaviors, ranging from taking care in details to calling/texting teammates who are absent (to ask if they are coming to class). Frequently, students even forget when the class period is over.

5. Conclusions and Future Work

Early results indicate that the Studio format is successful in eliciting improved test performance. Review of activities and comments from students indicate that they are thinking about engineering and the learning process in ways that are deeper than I had previously encountered. I am very encouraged and intend to continue using the Studio method indefinitely. I note that the Studio method does not stand on its own, but blends elements of Inverted Classroom, Mastery Based Learning, and Concept-based Learning, all of which provide foundation and context for what is done within the Studio format. Further work is required to refine the method and validate the results more rigorously. Future work will also report on specific details of both student and instructor 'epiphanies' and insights that have changed approaches to learning and teaching, of which I have many.

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Appendix. The Developed Activities

Activity 1: Exploring Forces and Vectors

A. Preliminary

1. What is the unit of measure on your spring scale? How is the scale divided? What do you think is the highest level of precision that you can expect to have?

B. One Scale

2. One person should take one spring scale and the ring (heavy washer), keeping the scale oriented parallel to the tabletop ("flat" or "horizontal"). Without touching the ring, except by the single scale, attempt to apply at least 20 N to the ring. What do you observe? Can you think of any principle or law of mechanics that applies to this situation?

C. Two Scales

3. Next, have two people each hook one scale to the washer. Pull to approximately half the capacity of the scale (again, parallel to the tabletop). Hold the scales steady over a large sheet of paper so that the other team members can record the measured value of each scale AND trace a sketch of the system on the paper. What do you observe about the readings and the way that the scales are oriented?

4. Interpret your observations in terms of a *Free Body Diagram*: that is, draw a sketch of only the ring, and then sketch how you think forces are acting on the ring. Use a ruler to draw each force to an appropriate *scale*. Again, is there a principle or law of mechanics that applies? Are your measurements perfectly precise, or is there some measurement error?

D. Three Scales

5. Now have three people each hook one scale to the ring (again, with all scales parallel to the tabletop). Attempt to achieve a "random" pattern such that the scales are not parallel to each other and they all have a different value. Then, as before, hold the scales steady over a large sheet of paper so that the other team member can record the values and trace a sketch of the system on the paper. After the sketch is made, add to your sketch some "central lines" that go through the centers of the scales (and meet at the center of the ring), so that you can determine the *angle* between each scale.

6. Draw the *Free Body Diagram* (FBD) of the ring. This time, take care to *draw each force arrow to scale in both length AND orientation*. At least one force arrow should be approximately 15 cm (6 in) long. Is there a principle or law of mechanics that applies? What happens if you try to add or subtract the numerically measured values of the scales? Does it make sense?

7. Draw a separate diagram of the *force triangle* of the three forces in the FBD. To help, consider cutting three strips of colored paper, one for each force. Each colored strip should have the same length AND orientation (angle or slope) as its corresponding force arrow. Now, like a simple puzzle, what happens if you put the strips (or draw the arrows) "head to tail"?

E. Vector Addition: Rectangular (Cartesian) Components

8. Write each force vector from Part D in Rectangular (Cartesian) components. That is, write each vector in the form $\underline{\mathbf{F}} = F_x\mathbf{i} + F_y\mathbf{j}$. Because all vectors should be expressed in the same reference system, *some of your component values should be negative*.

9. Now add the three vectors (add the *x*-components and *y*-components separately). What is your result? Explain and reflect.

F. Vector Addition: Method of Direct Trigonometry

10. Using your force triangle (Question 7, above), measure each angle inside the triangle with a protractor. Does the triangle satisfy the Law of Sine and Law of Cosine?

G. Final Reflection.

11. What did you learn in this activity? What surprised you? What is still "muddy" (not clear)?

12. How is the pace of the activity? The team dynamic?

Activity 2: Estimating and Calculating Two Forces

A. Preliminary

1. Explain why in two dimensions, two unknown forces can be solved from the equations of static equilibrium.

B. Geometry and Free Body Diagram

2. Imagine that you suspend an object of weight *W* from a washer, and that the washer is supported by two other strings or cables. Choose the angles that each cable makes with respect to the horizontal, such that (i), the angles are different by at least 10 degrees, (ii) the angles are not equal to each other, (iii) the two cables are not at right angles to each other, and (iv) each angle is at least 5^{o} away from 30^{o}, 45^{o}, and 60^{o}.

3. Sketch the FBD of the washer. Label each vector with a useful name.

C. Estimation

4. Assume that *W* is the given force (even though it's still "*W*"). Using what you learned in Activity 1, estimate the value of the other two forces using a graphical method. Do NOT attempt a detailed calculation. Show your results to the instructor before proceeding to the next question.

D. Equations and Calculation

5. Write each vector in terms of Cartesian components (**i** and **j**), using the symbolic expressions in your FBD. Then, write the equations of equilibrium in the "Standard" format.

6. Solve your equations in terms of the "given" value of *W* by hand calculation.

7. Solve the equations using the Excel Calculator. How do you do this if the value of *W* is not explicitly given?

E. Experiment

8. Find an object of approximately 2-4 lbs that you can hang. Suspend this weight from the washer. Then, fix two long strings to the washer, holding the system just in front of the whiteboard in the classroom. Align

each string according to your chosen angles above. Because the protractor is “small”, determine an equivalent “slope triangle” for each cable that you can draw on the board. Use the level to draw horizontal and vertical lines accurately. Take a photo.

9. When everything is lined up, attach a spring scale to each of the diagonal strings, and record the measurements.

10. How do the measured values compare with your calculated solutions?

F. Exploration

11. What happens to the force in each string if they are both nearly vertical?

12. What happens to the force in each string if they are both nearly horizontal?

*** Note: in either case, if you use the spring scales for evidence, please do not pull the springs past the capacity. ***

G. Final Reflection.

13. What did you learn in this activity? What surprised you? What is still “muddy” (not clear)?

14. How is the pace of the activity? The team dynamic?

Activity 3: General Reactions and Forces

A. Normal vs. Frictional Forces

1. Take a belt or similar object and attach it to something (or have someone hold one end). On the other end, pull on it in two different ways: first, grip it by wrapping your fingers around a flat section of the belt; second, make a loop and then pull on it with your arm or closed fist. Describe the difference between the two cases, and draw a corresponding FBD of the belt in each case.

2. Consider Activity 1 when you applied forces to the washer. Would you consider that the hook from the spring scale (or the string) pushes or pulls on the washer? What if you specifically consider what the hook (or string) is doing to the inner surface of the washer?

3. How can you use these ideas to pick up something that is very slippery, such as a slice of avocado, a heavy object with a soapy surface, or anything else that you can think of.

B. General Reactions

4. Use the Lego kit and other available materials to build a representation of each of the following reaction types explained in Module D2: cable, roller, pin/hinge, slot, fixed/built in end, moment-resisting collar. For each type, isolate a particular component from your model and draw its FBD. Then, write a short statement to explain what kind of motion is allowed, what kind of motion is prevented.

5. Find an example of each type that is part of a real object or system. This can be done by finding a physical example available to you, a photo of something that you take, or a photo from the internet. For each case, make a photo, sketch the FBD of the component or part of your system that has the corresponding reaction type, and name the adjacent object that is causing the reaction.

C. Springs

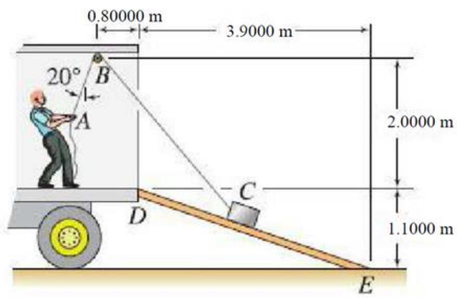
6. Determine the spring constant for one of the yellow spring scales that we have been using in class.

7. Find a real object that is not a conventional spring (i.e., not a coiled object), but which acts like a spring. Measure its spring constant.

D. Simple Pulley

8. Verify the "Law of the Frictionless Pulley" by passing a string around a smooth, round object (or get an actual pulley if you like). On one end, hang an object of known weight. On the other end, attach the spring scale. What does the scale read? Does it depend on the angle that you hold the side of the string with the scale?

E. Moving and Delivery Services: Design and Safety



Consider the system above that is designed to assist a worker to lift or lower a box on ramp attached to the back of a moving truck. Assume that the motion is slow so that the box is approximately in static equilibrium.

9. Assume that there is no friction on the ramp, and propose a reasonable value of weight for the box. Determine the value of the tension in the cable at three positions for the box (i) *E* (bottom), (ii) midpoint between *D* and *E*, and (iii) *D* (top). Include an appropriate FBD, equilibrium equations, and supporting calculations.

10. Based on your results, does this system assist the worker? Explain.

11. Now suppose that there is a coefficient of dynamic friction $m_k = 0.20$, and consider two cases at the midpoint of the ramp: (i) the box is being slowly pulled up, (ii) the box is being slowly lowered down. What is the tension in each case?

12. Can you think of any possible adjustments to any of the factors that would improve the functioning of the system? Test your hypothesis with some calculation. What are the practical considerations that would limit your options to adjust these factors?

13. How might the design of the system affect worker safety and wellbeing? Are there any regulations that might influence how the system is designed?

F. Final Reflection

14. What did you learn in this activity? What surprised you? What is still "muddy" (not clear)?

15. How is the pace of the activity? The team dynamic?

Activity 4: Introduction to Couples and Moments

A. General Explanations

1. According to the reading assignments (Modules D4), explain the general circumstance under which moments can arise.

2. Define a couple.

B. Experiments

Use one of the rectangular aluminum plates to do the following:

3. Choose any two holes at the corners. Pull on each hole using a string, paper clip, or similar object, in any direction. What do you observe? Repeat by choosing at least one different hole.

4. Repeat the above experiment, except this time, when you set up your pulling forces, start with both forces parallel to each other. As you pull, impose the condition that the two forces remain parallel to each other. Now what do you observe?

5. Hang the plate from one corner with your string or paper clip. Then, draw the Free Body Diagram of the plate, with the observed orientation of the plate carefully drawn. Hint: assume the plate is heavy. How many forces are on the FBD? Are there any prior activities that you have done that are similar, and which will help you understand exactly how the forces here should be drawn?

6. Now choose one of the corners of the plate and grip it tightly so that two edges of the plate are horizontal, and the other two are vertical. Draw the FBD of the plate in this orientation. Explain what you feel at the gripping point.

C. Calculation

7. Pick a random point somewhere on the plate. Then pick any corner, and imagine that you apply a force at that corner. Choose a hypothetical magnitude and direction that is not parallel to one of the edges. Calculate the moment of the force about the point.

D. Final Reflection

8. What did you learn in this activity? What surprised you? What is still "muddy" (not clear)?

9. How is the pace of the activity? The team dynamic?

Activity 5: Introduction to Couples and Moments

A. General Explanations

1. According to the reading assignments (Modules D5), explain there are three equations of equilibrium for a rigid body in 2D.

B. Experiments

Use one of the rectangular aluminum plates to do the following:

2. Weigh the plate with a spring scale and carefully locate the center of mass.

3. Then, holding the plate ‘vertically’,

    a. one person should pass a small bolt through one of the corners and hold it as a “pin” connection.
    b. Another person should place a spring scale in the hole diagonally opposite.
    c. Then, select two arbitrary angles, avoiding right angles or 45º angles: one for angle of the bottom edge of the plate with respect to the tabletop, and the other for the angle of the scale with respect to one edge of the plate. To help measure the angles carefully, take a photo of this configuration using a wall, whiteboard, or a large piece of paper as a background.
    d. Record the angles and the force in the spring scale.

4. To analyze,

    a. Draw the FBD of the plate in this configuration.
    b. Write and solve the equations of equilibrium.
    c. Redraw the FBD with the forces drawn to scale, based on the solution.
    d. Draw the force polygon to scale, based on the solution.

5. Explain why the plate does not rotate, even though you are not directly applying a reaction torque anywhere.

C. Exploration

6. Identify a streetlight or stoplight that has a basic ‘overhanging’ design, i.e., a vertical post anchored to the ground, and then a horizontal arm that supports the light. Using any combination of data searching and direct measurements (yeah, go out and take a look!), then complete the following steps:

    a. Draw the FBD of the post. In this case, consider the weight of the elements. How should you model the reactions at the base?
    b. Write and solve the equations of equilibrium.
    c. Redraw the FBD with the forces drawn to scale, based on the solution.
    d. Draw the force polygon to scale, based on the solution.

D. Final Reflection

7. What did you learn in this activity? What surprised you? What is still “muddy” (not clear)?

8. How is the pace of the activity? The team dynamic?

Activity 6: Consistent FBDs of Multiple Connected Bodies

A. Recap Activity 5

1. Repeat the calculation of your Sum of Moments equation, this time by using a coordinate reference aligned along the edges of the plate. Comment on if the result is the same or different.

B. Background

2. What is the key principle of Newton that is presented in Modules C1, and state it.

3. When drawing the FBD of an entire connected system, do not draw _________ .

C. Exploration

4. Examine the clothespin and consider it to consist of three discrete elements: two levers and a torsional spring. Draw consistent FBDs of each element under the following scenarios:

    a. Resting on the table such that gravity is parallel to the axis of rotation of the spring.
    b. Your fingers pinching the ends to open it.

    * Is weight a necessary force in these scenarios?

5. Now hold an object by pinching it with the clothespin. Draw consistent FBDs of each element of the clothespin and the object that you are holding.

6. Return to Activity 3 and repeat or redo at least one of the Lego exercises, but this time drawing consistent FBDs of at least two joined elements.

D. Final Reflection

7. What did you learn in this activity? What surprised you? What is still “muddy” (not clear)?

8. How is the pace of the activity? The team dynamic?

Activity 7: Frames and Machines

A. Background

1. Based on Modules C4, Characterize the number of unknown reactions and the corresponding number of independent equations of equilibrium for a statically determinate frame.

B. Pliers

2. Examine a pair of pliers and assume that it consists of three elements: two handles and a pin. Do a “reverse” test by applying two spring scales to the end of the handles and two spring scales at the end of the “jaws”. Record the values of each scale.

3. Draw the following consistent FBDs: each handle, the pin, and the entire pliers assembled.

4. Now follow the method of Modules C4 to predict the relative values of the applied forces as well as the forces between the pin and each handle. Note that you will need to assume that one of the applied forces is “given”. How do the calculations compare with what was observed?

5. Redraw each FBD such that the forces at the pin are expressed as a single resultant (magnitude and direction), AND are drawn on the appropriate section of the surface of the pin (i.e., where the interaction is principally occurring).

6. Explain why pliers “work”.

C. Chair

7. Examine the model chair. Make an accurate sketch of its 2D profile, including measurements of the dimensions and angles.

8. Assume the chair has no weight but has Mario Lemieux sitting or standing. Draw a FBD of the following:

a. The entire system. Assume Mario is heavy and that that chair is light.
b. Mario
c. The chair as assembled.
d. Each element of the chair

* You will need to make some modeling assumptions to make sure that the total unknowns is equal to the number of independent equations of equilibrium. Are there any bodies that are best represented as a 2-force member? Is friction important anywhere?

*** Check in with the instructor before proceeding. ***

9. Solve for the reactions using the following procedure:

   a. Determine the reactions of the chair on Mario. Show all three equilibrium equations, and you can solve these by hand or using the solver.
   b. Apply Mario's 'equal and opposite' reactions on the chair.
   c. Determine all of the unknown reactions on each element of the chair. Show all 9 equilibrium equations. You probably want to use the solver in this case.

10. What would happen to the system if you remove the short metal link between the seat of the chair and the leg?

D. Final Reflection

11. What did you learn in this activity? What surprised you? What is still "muddy" (not clear)?

12. How is the pace of the activity? The team dynamic?

Activity 8: Trusses

A. Background

1. Play with the popsicle stick models and explain why triangles are a useful structural form.

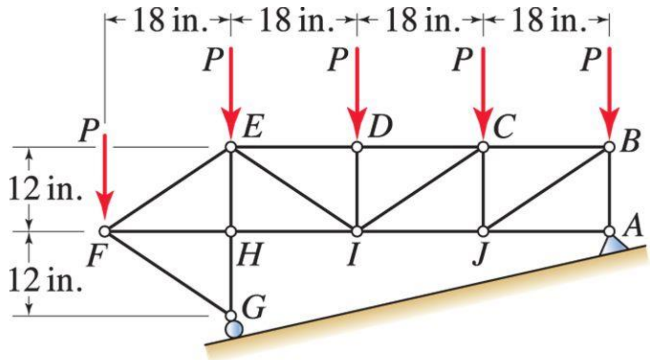
2. In an ideal truss, every member is considered to be a …

3. Write a brief comparative essay: compare and contrast problem-solving procedures for trusses vs. frames.

4. In the method of joints, why does each joint have only two equations of equilibrium, whereas each section has three equations of equilibrium (in 2D)?

B. Analysis

Consider the following truss with P = 100 lb.



5. Use the Method of Joints to determine the force carried by each member. You may use the Solver to solve your equations. Summarize the results on a sketch.

6. Verify the values of the reactions using a FBD of the entire truss.

7. Use the Method of Sections to verify the forces carried by members *CD*, *CI*, and *IJ*.

D. Exploration

8. Find at least 4 examples of trusses that you observe in your everyday surroundings. Document with photos and short descriptions.

E. Final Reflection

9. What did you learn in this activity? What surprised you? What is still "muddy" (not clear)?

10. How is the pace of the activity? The team dynamic?