Designing Active Learning Environments

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Switching from lecture to active learning is an act of courage, but the growing consensus of research on the benefits of active learning is difficult to ignore.

"...teachers possess the power to create conditions that can help students learn a great deal -- or keep them from learning much at all. Teaching is the intentional act of creating those conditions..." - Parker Palmer (1998)

Introduction

What conditions help students learn? How do we design a course environment to foster those conditions? How can we tell if students are learning what we teach? The advent of massive open online courses (MOOCs) and flipped classrooms has reinvigorated discussion of these questions in higher education. At the same time, research by Kuhl and her colleagues (2003, 2010) demonstrates that even infants learn better from engagement with a live person than they do from watching recordings. Kuhl et al.'s research resonated with our own experience that university students also learn better from interactive engagement than from passive viewing of lectures. Recent neuroscience and education research on learning and memory confirms the benefits of active learning, which includes techniques such as collaborative in-class problem solving (Ambrose et al., 2010; Brown et al., 2014). This article highlights research on active learning and describes our implementation of it in engineering courses.

DJ Prof versus Popstar Prof

Blending active learning with some lecture and external resources such as textbooks and videos creates the conditions needed for a student-centered learning environment. In a musical analogy, the professor in a student-centered course becomes the DJ, mixing together multiple modes of instruction for the students' benefit (**Figure 1**). In contrast, the professor in a traditional lecture course is the soloist or pop star, delivering content with minimal feedback from students. Although many faculty worry that changing from lecture to student-centered learning means that they will not have time to cover as much material, the data indicate that students master more material despite the professor covering less. Switching from lecture to active learning is an act of courage, but the growing consensus of research on the benefits of active learning is difficult to ignore.

Research on Learning

Two recent books provide guidance on creating effective conditions for student learning in university-level courses. *How Learning Works* (Ambrose et al., 2010) presents seven principles for teaching derived from the literature on psychology, anthropology, and organizational behavior. Ambrose et al.'s first principle is "Students' prior knowledge can help or hinder learning." The book's discussion of this principle (p.4) highlights the importance of addressing students' prior misconceptions to help them learn new material. Simply informing students of their miscon-

Figure 1a *Figure 1b*

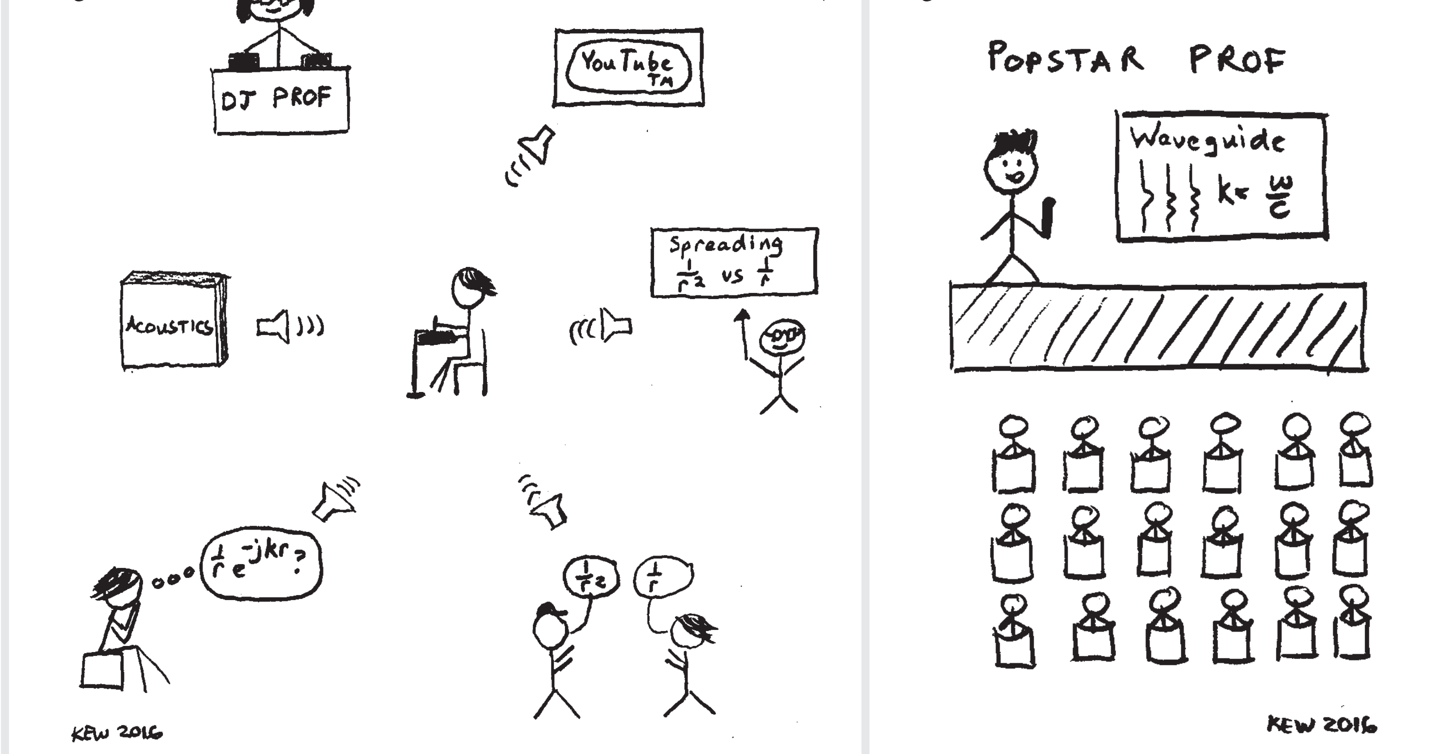

Figure 1*. a: In a student-centered course, DJ Prof mixes multiple modes of instruction: Think-Pair-Share exercises, lecture, video examples, and reading assignments. b: In an instructor-centered course, Popstar Prof presents a lecture with little or no feedback from the students.*

ception is rarely sufficient to dislodge that misunderstanding. A better approach is to have students confront their misconceptions through exercises that ask them to predict the outcome of an experiment and then carry out that experiment and analyze the results. *Make it Stick* (Brown et al., 2014) grew out of a 10-year project to apply cognitive science research to improve education. Brown et al. assert that many people use suboptimal learning strategies that are not supported by research, and that "the most effective learning strategies are not intuitive" (p. ix). For example, Brown et al. observe that "trying to solve a problem *before being taught the solution* leads to better learning," (p. 4, emphasis original). Neither of these books provides step-by-step instructions for designing and implementing courses. Rather, they present a set of general principles, derived from research, to create conditions for effective learning.

Many university courses are still taught in the standard lecture format. The lecture is an ancient form of instruction, dating back to at least medieval times in western European universities (see **Figure 2**). As Professor Joe Redish of the University of Maryland points out, lecture predates the printing press (Hanford, 2011). An instructor would read a manuscript to students so that the students could make copies for themselves. In a world without printed books, this makes perfect sense. In a world with not only books but also an Internet full of articles, podcasts, TED talks (www.ted.com), and YouTube videos (www.youtube.com), is lecture the best way to educate students? To answer this question, consider several analyses of student learning in science, technology, engineering, and math (STEM) courses.

Benefits of Active Learning

Hake (1998) compared student learning in traditional lecture-based physics courses with learning in *interactive engagement* (IE) courses. He defines IE courses as those that are designed to "promote conceptual understanding through interactive engagement of students in heads-on (always) and hands-on (usually) activities which yield immediate feedback through discussion with peers and/or instructors" (Hake, 1998, p. 65). For our purposes, we consider IE to be synonymous with active learning. Hake focused on Newtonian mechanics courses and used data from the force concept inventory (FCI) (Hestenes et al., 1992) in the analysis. A concept inventory (CI) is a multiple-choice exam designed to test student understanding of the core concepts in a subject area. CI questions require few, if any, computations, and the wrong answers (distractors) elicit common student misconceptions. In Hake's (1998) study, students took the FCI twice: before the start of the course and then at its conclusion. Hake used the pretest and posttest averages to define the average gain in conceptual understanding due to instruction: gain = (Post-Pre)/(100-Pre). The gain represents

Figure 2. Painting by Laurentius de Voltolina dating from the second half of the 14th century. Judging from this illustration, student distraction and dozing during lecture are not modern problems. Photo from commons.wikimedia.org.

the fraction of the available improvement that was attained during the course. Hake's survey of over 6,000 students in mechanics courses showed that the average gain for traditional lecture courses was 0.23. That is, students learned less than 25% of what they didn't know (**Figure 3**). In contrast, active-learning courses had an average gain of 0.48.

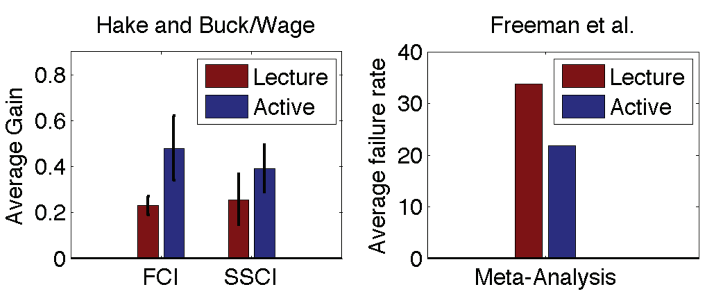

Figure 3. Active learning increases how much students gain and reduces failure rates. Left: Gains (means ± SD) for lecture and active courses as measured by two concept inventories, the force concept inventory (FCI) and the signals and systems concept inventory (SSCI). The FCI results are from Hake's analysis (1998) of 14 lecture courses and 48 active courses. The SSCI results are from our own analysis of 28 lecture courses and 34 active courses. Right: Freeman et al.'s (2014) results from a meta-analysis of the failure rates in lecture and active learning courses in science, technology, engineering, and math (STEM).

Are Hake's results applicable to courses other than Newtonian mechanics? Two of us (JRB and KEW) developed the signals and systems concept inventory (SSCI), which is designed to measure conceptual understanding in undergraduate linear systems courses (Wage et al., 2005). The SSCI assesses students' understanding of Fourier analysis, convolution, filtering, and sampling. **Figure 3** shows the results of our analysis of gain for the SSCI. Similar to Hake's (1998) results, the SSCI analysis shows a significant increase in gain for active learning courses.

Recently, Freeman et al. (2014) prepared a meta-analysis comparing traditional lecture and active learning for STEM disciplines. Based on data from 225 studies, they showed that student performance on examinations in active-learning courses increased by 0.47 standard deviations over examinations in traditional lecture courses. Using CI data from 22 studies, including those for the FCI and SSCI, the authors concluded that active learning improves the final CI score by 0.88 standard deviations, indicating that students in active-learning courses demonstrated greater improvement in conceptual understanding. Finally, as **Figure 3** illustrates, Freeman et al. showed that the failure rate for students in traditional lecture courses was 33.8%, whereas the failure rate in active-learning courses was 21.8%. Based on this meta-analysis, Freeman et al. concluded that active learning is the "preferred empirically validated teaching practice" and suggested that the traditional lecture should no longer be used as the control in research studies.

Why Is the Traditional Lecture So Ineffective?

A skilled lecturer can present material in such a gloriously smooth fashion that everything seems clear to even the most naive listener. But is this clarity real? Or is it an illusion? Watching an expert perform in any domain, be it technical, musical, or athletic, can mislead us into thinking we can easily duplicate their performance. This "illusion of knowing" (Brown et al., 2014, pp. 102-130) is typically dispelled the moment we attempt the same feat. The typical college classroom has more illusions floating around than Hogwarts School of Witchcraft and Wizardry (Rowling, 1999). The students are under the illusion that they understand what the instructor is saying. The students often don't realize that their understanding is a mere mirage until they get home and start the homework. At that point, there is no one around to answer his or her questions. The instructor is under the illusion that the lecture is clear and that all students understand everything perfectly. Instructors often don't realize this was an illusion until they grade the midterms and sometimes not even then. If most of the exam questions are taken from the homework, students will be able to answer them by rote memorization. However, many students will lack the understanding to apply the concepts correctly in new contexts.

Why Does Active Learning Work Better Than Lecture?

Active learning seeks to minimize the illusion of knowing and spark questions when there are instructors available to answer. Guided by research, active learning also acknowledges that students' prior knowledge affects their ability to learn and tries to bring misconceptions to the fore to correct them. In the analysis leading to the development of the FCI, Halloun and Hestenes (1985) concluded that conventional lecture courses do not force students to confront their misconceptions. This conclusion motivated significant research in physics education and the development of active methods of instruction, including Mazur (1997). These active methods are consistent with the principles summarized in *How Learning Works and Make It Stick*.

The authors of this article teach signal processing and linear systems theory courses. Students in these courses encounter fundamental acoustical concepts like impulse response, frequency response, filtering, and Fourier analysis for the first time. Examples drawn from music, speech processing, psychoacoustics, and bioacoustics make the mathematics come alive for students. For instance, one of the authors begins the semester by drawing a block diagram of an MP3 encoding system and then identifies which chapters in the textbook address each block. These courses can open doors to a life in acoustics research for students as similar courses did for the authors. We believe that the pedagogical lessons learned teaching these courses transfer naturally to other acoustics courses.

In the remainder of this article, we describe a variety of active learning techniques that are supported by research, and we illustrate these techniques using examples from our own courses. We hope the rest of the article will motivate the reader to try some of these techniques. The final section provides ideas and a list of resources for getting started.

Elements of Active Learning

Although a variety of definitions for active learning exist, we choose to define the term broadly for the purposes of this article. Active learning, as the name implies, refers to classroom activities in which students are engaged in the learning process (Prince, 2004). This is in contrast to the traditional lecture, where it is assumed that students are listening passively to material and that engagement does not move beyond copying notes. Active learning brings engagement with the material into the classroom, where instructors can provide immediate feedback rather than relegating hands-on practice to homework that is often completed alone. Collaborative learning is a subset of active learning, requiring students to work together to understand concepts, solve problems, and master material. Active-learning implementations often vary across disciplines. Common forms of active learning in STEM courses include group problem solving, peer instruction, conceptual discussions, and laboratory explorations. Many active-learning techniques can be implemented in such a way that students first engage individually with the material and then engage with peers to discuss and defend their conclusions. A common approach is the Think-Pair-Share technique (Lyman, 1981; Johnson et al., 1998; Barkley et al., 2005) in which students first work on a problem or question alone, then join with a peer to discuss responses, and finally share collective responses with a larger group or the full class.

Making room for active learning in class requires pushing some traditional lecture out of the classroom. Moving lecture outside the class to allow time for active learning has motivated the now popular "flipped classroom" model. Although discussion of the flipped classroom often focuses on the means of delivering content that is flipped out of scheduled class meetings, the major pedagogical opportunity is the new activities that are flipped in to the class. That said, the displaced lecture content must appear in some form, and it can be delivered in a variety of ways. An increasingly popular approach to content delivery is via online videos. Videos allow students to absorb material at their own pace and to rewatch content several times if needed. They can also satisfy students' unquenchable thirst for examples. Videos are not the only option for content delivery, however. Lecture may also be flipped out of the classroom via more traditional delivery, reading the textbook. Learning new technical material by reading is an essential skill for a successful career. Technical fields progress rapidly, and even highly prepared students will need to learn new material within a few years of graduation. The fundamental medium of exchange for advanced technical ideas is still the written word (and written equation). We believe that failing to teach technical reading skills to students is doing them a profound disservice and setting them up for rapid technical obsolescence.

In advocating for active learning, we are not suggesting that lecture be abandoned entirely. For lecture to be effective, however, students must be prepared to absorb the material presented. In *A Time for Telling*, Schwartz and Bransford (1998) described how students need relevant prior knowledge to benefit from lecture-based instruction. To learn from a lecture describing techniques for solving problems, for example, students must first become familiar with the problems of interest, perhaps by trying to solve problems and identifying the challenges they need to address. Hence, active learning and lecture can and should coexist in college teaching. The professor, acting as DJ (**Figure 1**), must carefully mix these components to maximize student learning.

Students must complete the assigned reading (or assigned viewing) before class for active learning to succeed. A common approach for motivating students to prepare for class is to start each day with a short quiz on the assigned material. Equally important is to teach students about active reading and watching. Technical material cannot be absorbed with the casual reading or viewing habits students use for Facebook (www.facebook.com) or Netflix (www.netflix.com). Students should be encouraged to take notes on the content and to work problems while reading or viewing, covering the answer (or pausing the video) to see if they can complete a problem on their own. They should also be encouraged to engage in frequent self-quizzing by recalling definitions and formulas as well as solving new problems (Brown et al., 2014, pp. 34-45). These techniques will help them retain the material for use in class and beyond.

Implementing Active Learning

This section describes our implementation of active learning in engineering courses. The first paragraph describes the common structure of our active learning courses. Subsequent paragraphs discuss the variants in greater detail. All three of us begin with a short graded quiz to hold the students accountable for the required reading. We then review the reading quiz, providing an outline and overview of the topic for that day. We lecture in short 10- to 15-minute segments, reviewing fundamental or challenging aspects of the material. Students spend a majority of the time working collaboratively on problems in pairs or small groups while instructors (and TAs if available) circulate among the groups answering questions, providing feedback, and eavesdropping on students' conversation to assess their misconceptions. Grading these in-class student exercises holds students accountable and keeps them focused. Weekly homework assignments of more complicated problems build on the simple in-class problems and challenge students to develop their knowledge and skills in novel contexts. This high level structure is essentially unchanged from our prior descriptions of active-learning courses (Buck and Wage, 2005).

Our approach to the reading quizzes has evolved since 2005. The quiz may be on paper, online, or use automated response systems, generically known as "clickers," depending on class size and resources. The quiz may be open notes or closed book depending on the goals of the course. Open notes rewards note taking in active reading. Closed notes emphasizes mastery of fundamentals like complex number arithmetic. The quiz may include questions from the previous class to encourage review of previous material.

We vary in our lecture segment delivery as well. In some classes, we repeat two or three cycles, interleaving the short lectures with problem-solving sessions. In other classes, we deliver a short lecture at the start and then spend the rest of the class period in student problem-solving, possibly interrupting the student discussions to address a common misconception. Another strategy is to start with a problem-solving session directly after the reading quiz, break for a short lecture, and then return to problem solving. This approach exploits the deeper learning and longer recall activated by first struggling with a problem before learning the solution (Bjork and Bjork, 1992; Brown et al., 2014, pp. 67-101).

The in-class assignments also vary in format, scope, and assessment. For large sections in lecture halls poorly suited for group work, the students work multiple-choice problems in pairs, responding using clickers. Large-section problem-solving sessions may also include peer instruction through discussion, such as the Think-Pair-Share exercise cited above. In rooms configured for group work (**Figure 4**), students work short pencil and paper exercises in groups of three to four. When sufficient space is available, groups work on the board, facilitating discussion with peers and feedback from the instructor.

Our assessment strategies for the in-class problems try to balance low-stakes formative feedback for the students with sufficient group accountability to keep students engaged. In some classes, we grade the in-class problems on a tertiary scale of check/check plus/check minus. Other classes encourage group accountability by requiring all of the mem-

Figure 4. George Mason University's Active Learning with Technology classroom is designed to support collaborative, student-centered learning. The whiteboards on the walls and projection to dedicated flat-screen displays encourages student interactions. Photo from Creative Services/George Mason University, with permission.

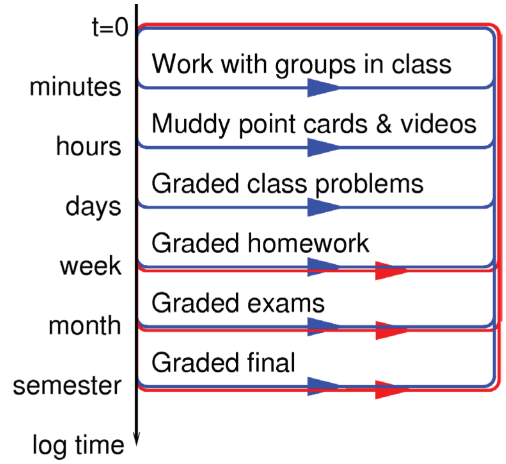

Figure 5. Active-learning classes (blue) provide feedback to students about their understanding on many short timescales in addition to the traditional homework assignments and grades. Traditional lecture classes (red) only provide feedback on the longer timescales of weeks and months, resulting in less effective memory formation.

bers of each group to submit their collaborative solutions, then grading one randomly chosen paper from each group (Johnson et al., 1998).

"Muddy point" cards offer an opportunity for students to provide feedback to instructors. We give students index cards at the end of class and ask them to write down something that is still confusing to them about the day's material. The cards are anonymous and provide immediate feedback to the instructor about the students' understanding. We can address the contents of the cards either by a short email later that day or by recording a video with some additional examples or instruction (see next section).

The integration of these active-learning techniques provides students with feedback on many time scales, shown in **Figure 5.** Starting from the introduction of a topic in class ($t = 0$), students receive feedback on timescales of minutes, hours, days, weeks, and months. Frequent feedback and recall leads to stronger memories, resulting in better student mastery of material (Brown et al., 2014, pp. 33-39). Instructors are also receiving feedback about the students' understanding on all of these timescales, allowing them to react and address misconceptions early in the learning process before they become entrenched (Brown et al., 2014, pp. 44). In contrast, a traditional lecture course provides feedback to students only on the longer timescales of weeks and months.

Video Killed the Lecture Star

The largest change to our implementation of active learning in the decade since publishing Buck and Wage (2005) is the incorporation of YouTube video lectures to supplement the classroom instruction. Ideally, these video lectures run 10-15 minutes in length. Our video lectures do not just duplicate classroom lectures but instead present examples or additional exposition to address a specific student misconception identified while grading in-class problems or homework or while reading muddy point cards. Some recordings cover examples we set aside from our old lecture notes to free time for in-class problem sessions. "More examples please" is a perennial refrain on student evaluations, and the videos offer one way to address this request. Finally, some recorded lectures cover secondary material that students should be able to digest once they master the major points in class. For example, after teaching the fundamentals of the Z-transform during the short in-class lecture, we relegate the discussion of various transform properties to video lectures for later viewing.

Our videos opt for a simple presentation. Inspired by the popular Khan Academy videos (www.khanacademy.org), we show writing on screen using a whiteboard program along with synchronous audio narration. This format emulates the experience of an instructor and student sitting side by side with a piece of paper during office hours. We believe this approach encourages student engagement. Moreover, we believe that other common presentation modes for instructional videos such as lecture hall recordings, narrated slides, or talking head videos with slides implicitly put students in the mind frame of more passive experiences, such as attending a large lecture or watching TV. Guo et al.'s (2014) study of MOOC videos supports our intuition on presentation format. Guo et al. found that short Khan-style videos and an informal style improved student engagement in online videos over narrated slides or lecture hall recordings.

Contrary to popular belief, producing instructional videos need not demand the time and resources required to

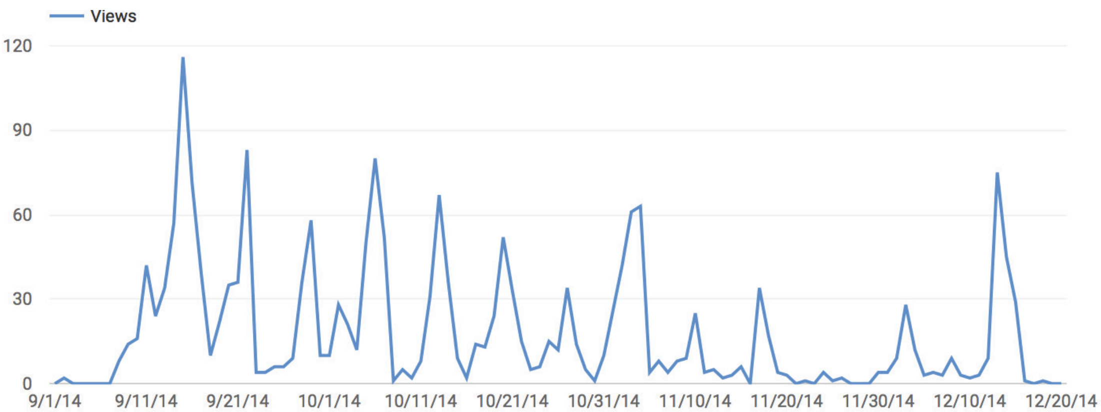

***Figure 6.** Daily viewing of the ProfJohnBuck YouTube channel during the Fall 2014 semester with an enrollment of 67 students. The viewing data clearly show a strong signal in a seven-day period, consistent with the weekly homework due every Tuesday. The exams on 10/7, 11/4, and 12/15 increased student viewing.*

produce an Olympic opening ceremony pageant. There are many ways to capture synchronous screen and audio recordings. One author (KEW) employs the Doodlecast iPad app (http://doodlecastpro.com) with a wired clip-on microphone. Another author (JRB) uses the TechSmith (https://www.techsmith.com) capture software with a writing tablet, whiteboard program, and wired headset. The Khan Academy FAQ (https://goo.gl/9S7Lw2) lists the equipment Sal Khan uses to make his videos. Inspired by Sal Khan's comments (2013), we also choose not to edit our videos but leave our self-corrections in the recordings, reinforcing the informal in-person style. Students' responses to the videos were largely positive right from the start, rough as our early efforts appear to us now.

YouTube analytics confirm that students devote considerable time to watching the videos. YouTube does not provide individual students' viewing data but does report aggregate viewing by state as a function of time. We use this aggregate data from our university's home state during the dates of the semester as our best estimate of total viewing data. The combined Massachusetts viewers during the Fall 2013, Fall 2014, and Fall 2015 semesters spent 24,750 minutes watching videos on the ProfJohnBuck channel (https://goo.gl/EoPQpG). The combined enrollment of the UMass Dartmouth linear systems classes during these three semesters was 189 students, yielding a rough estimate of 130 minutes/student of viewing. For a class that meets 150 minutes/week, this average represents nearly a week of additional instructional time. Although we cannot be certain that all the Massachusetts viewers are students in these classes, the strong correlation between the YouTube time series and assignment due dates (**Figure 6**) suggests that the viewing data are predominantly students. End of semester evaluations for these three semesters also support this interpretation. For each semester, at least 60% of the students reported watching "some," "most," or "all" of the videos, and at least 75% of the students reported that the videos were "helpful" or "very helpful."

An unanticipated dividend to recording these videos is their popularity with a broader audience. The combined worldwide viewing for the ProfKathleenWage (https://goo.gl/4eER4C) and ProfJohnBuck channels over the last 30 months exceeds 500,000 minutes.

Although some instructors in flipped classrooms deliver all of the preclass preparation via video lectures, we remain conflicted about completely removing reading from our courses. Our sense is that most of our students would prefer to watch a video than read a textbook. However, we strongly believe that technical reading skills are essential, and we are concerned that requiring viewing without any reading will not equip our students with the self-directed learning skills required for long-term success.

The Road Forward

Where to go from here? If you are skeptical of the empirical evidence for active learning provided by Hake (1998), Buck and Wage (2005), and Freeman et al. (2014), then find a concept inventory for your course (Foundation Coalition, 2008) and administer it using the pre-/post- protocol described above. If there isn't a concept inventory for your area, read the FCI or SSCI to get a feel for how CIs work, then write a few conceptual questions of your own and give them to your students. Listen to your students' explanations of their answers and learn what misconceptions they still retain after taking your course. We've done this exercise ourselves, and it was eye opening.

If you are convinced by Hake (1998) and Freeman et al. (2014) or intrigued by our description of active learning, there are a number of ways to get started. One of us started by assigning a short "warm-up" problem at the beginning of class that built on material covered in a previous lecture. This gave students some practice in applying the concepts and gave us the chance to observe their confusions. The warm-up problems didn't take much time, and they provided both students and faculty with useful information. If you'd like to learn more about designing active classrooms, there are several resources we have found to be very useful. In addition to Mazur's classic book (1997), the boxed insert lists three resources for getting started with active learning. The resources in the insert provide low-risk and relatively painless entry points into active learning, but perhaps an equally valuable resource is a group of like-minded colleagues with whom to share the journey. One challenge for instructors is committing the time necessary to implement, assess, and revise new techniques in their courses. A community of practice populated by instructors exploring similar techniques can provide ongoing support and accountability during the process. Education theorist Etienne Wenger (2016) describes communities of practice as "groups of people who share a concern or a passion for something they do and learn how to do it better as they interact regularly."

Online Resources for Starting with Active Learning

1 Hanford, E. (2011). *Don't Lecture Me.* American RadioWorks Podcast, September 2011. Available at https://goo.gl/u70FDp.

2 Mahajan, S. (2009), *Teaching College-Level Science and Engineering*. MIT OpenCourseware. Available at https://goo.gl/c3YJBJ.

3 Bruff, D., McMahon, T., Goldberg, B., and Campa III, H. (2014). *An Introduction to Evidence-Based Undergraduate STEM Teaching*. Center for the Integration of Research, Teaching, and Learning. Available at https://goo.gl/w0hssk.

Recent work in STEM faculty development has produced a model for ongoing teaching development groups to support adoption of evidence-based teaching practices. The SIMPLE design model builds on research results in both K-12 and college professional development (Jamieson and Lohmann, 2009; Loucks-Horsley et al., 2010). SIMPLE teaching development groups are guided by five principles: sustainable, incremental change, mentoring, people-driven learning environments, and design (Nelson and Hjalmarson, 2015). SIMPLE groups require very little infrastructure and are often realized as a group of faculty meeting over a weekly (or monthly) lunch to discuss new strategies they're using in their classes, share tips, and provide support. Creation of a community of practice can transform the often-isolating experience of trying new teaching strategies into a rewarding collaborative effort in which instructors learn from each other's challenges and successes.

Biosketches

John R. Buck is a Professor in the Electrical and Computer Engineering Department at the University of Massachusetts Dartmouth. His research studies signal processing, underwater acoustics, animal bioacoustics, and engineering education. John received his PhD from the MIT/ Woods Hole Oceanographic Institution Joint Program. He was a Fulbright Senior Fellow in Australia in 2003-2004 and received the 2005 IEEE Education Society Mac Van Valkenburg Early Career Teaching Award.

Kathleen E. Wage is a signal processor whose current interests are ocean noise, underwater acoustics, and engineering education. She is an Associate Professor of Electrical and Computer Engineering at George Mason University, Fairfax, VA. Kathleen obtained her BS in electrical engineering from the University of Tennessee, Knoxville and her MS and PhD in electrical engineering from the MIT/ Woods Hole Oceanographic Institution Joint Program. She received the 2008 IEEE Education Society Mac Van Valkenburg Early Career Teaching Award. Kathleen spent 55 days at sea for the PhilSea experiments and wishes the Olympic Committee would recognize "Sonobuoy Tossing" as an official sport.

Jill K. Nelson is an Associate Professor of Electrical and Computer Engineering at George Mason University, Fairfax, VA. Her disciplinary research lies in statistical signal processing, specifically detection and estimation in target tracking and physical layer communications. Her pedagogical research focuses on faculty development as a way to broaden use of evidence-based practices in STEM teaching. Jill earned a BS in electrical engineering and a BA in economics from Rice University, Houston, TX, and an MS and PhD in electrical engineering from the University of Illinois at Urbana-Champaign. She received the 2014 IEEE Education Society Mac Van Valkenburg Early Career Teaching Award.

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