We must teach more effectively: here are four ways to get started

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ABSTRACT **Research on how people learn shows that teaching using active learning is more effective than just lecturing. We outline four concrete ways instructors can begin to apply active learning in their teaching: backward instruction design; expecting students to learn more than facts; posing "messy" problems for students to solve; and expecting students to talk, write, and collaborate. Each tactic is supported with references demonstrating its efficacy and advice and links to resources for getting started with active learning.**

Monitoring Editor
Doug Kellogg
University of California, Santa Cruz

Received: Mar 17, 2015
Revised: Apr 13, 2015
Accepted: Apr 22, 2015

INTRODUCTION

No scientist wanting to remain at the leading edge of a field would use a research technique judged no longer as effective as an alternative. Shouldn't we apply the same standard to teaching? Research on how people learn (National Research Council [NRC], 2000; Singer and Smith, 2013) supports a clear conclusion: in contrast to a traditional lecture course, teachers using "active-learning" techniques improve student performance in science, technology, engineering, and mathematics (STEM) subjects. Scores on exams and conceptual assessments increase, while at the same time, students, especially from groups traditionally underrepresented in STEM subjects, are less likely to fail or withdraw (Prince, 2004; Haak *et al.*, 2011; Ruiz-Primo *et al.*, 2011; Freeman *et al.*, 2014). So, why don't more instructors use active learning? Because we teach as we were taught, and few of us were taught via active learning, except perhaps in a laboratory or field setting. How, then, do we master the techniques of this better way of teaching?

DOI/10.1091/mbc.E13-11-0675

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Abbreviations used: AAAS, American Association for the Advancement of Science; NRC, National Research Council; STEM, science, technology, engineering, and mathematic's.

Let us start with a definition. Active learning is when the instructor stops talking and students make progress toward a learning objective by actively doing something, such as working on a problem in a small group or using "clickers" to answer a conceptual question. Good sources for these techniques include the following:

- Biology education literature (e.g., ASCB's journal, *LSE*: www.lifescied.org),
- National Academies Summer Institutes (www.academiessummerinstitute.org),
- Online courses (e.g., Introduction to Evidence-based Undergraduate STEM Teaching: www.coursera.org/course/stemteaching), and
- Centers for teaching and learning (e.g., Science Education Initiatives at the University of British Columbia: www.cwsei.ubc.ca).

These resources provide evidence-based recommendations to improve student learning (Allen and Tanner, 2005; American Association for the Advancement of Science [AAAS], 2011; President's Council of Advisors on Science and Technology, 2012). In this paper, we offer four ways instructors can begin to apply active learning in a class.

DESIGN A COURSE BACK TO FRONT

Backward design starts with course-level learning goals instead of a subject's content (Wiggins and McTighe, 2005; Allen and Tanner, 2007). What do we want students to be capable of when a course ends: Thinking critically? Evaluating primary literature? Understanding the energetics of biochemical reactions? Learning goals lead to specific objectives—what students do to demonstrate that they have achieved desired goals. For example, how would we know whether students can think critically? Perhaps because they can evaluate whether a data set supports a conclusion. How would we know whether students understand the energetics of biochemical reactions? Perhaps they can predict whether an enzyme is likely to play a regulatory role in metabolism according to the thermodynamics of the reaction it catalyzes. Objectives define the desired student performance. Students should practice that performance (e.g., analyzing data sets, predicting regulatory enzymes in a pathway) and get feedback from instructors, teaching assistants, or peers. As students practice, feedback helps them learn what they are doing correctly and incorrectly so that they can adjust.

Designing backward takes time and practice, so using a guide helps (Allen and Tanner, 2007). Instructional materials developed using a backward design are available in *LSE* or other journals (e.g., *Advances in Physiology Education*). *CourseSource* (www.coursesource.org) is a new journal of teaching resources that align with scientific society–approved learning goals. ASCB-approved goals for a cell biology course can be found here: www.coursesource.org/courses/cell-biology. It is not necessary to reinvent an entire course; one goal, objective, or lesson at a time is a good start. Begin with a concept that students struggle most to learn Smith and Tanner (2010), that is most important, or that would be most troubling if students do not understand it after completing the course (Garvin-Doxas *et al.*, 2007; Coley and Tanner, 2012). Also, make sure that learning goals, objectives, tasks (how students will practice), and assessments (how students will get feedback and be graded) align. If an assessment tests students' factual knowledge, was that the aim? If exams demand a higher level of thinking, did students have opportunities to practice that level of thinking and get feedback on their performance?

AIM HIGH—BEYOND JUST THE FACTS

Students can memorize and then answer fact-based questions without understanding why facts are important or how they connect. Knowledge of every fact in a textbook is not necessary to grasp fundamental ideas in biology. Still, students must master some facts to be biologically literate. The *Vision and Change in Undergraduate Biology Education* report (AAAS, 2011) presents the overarching main concepts that students should understand. These concepts can be used to decide which facts to teach and which may be nonessential. As noted earlier, life sciences societies also offer guidance through *CourseSource* on what is essential to learn.

To learn more than facts, students often need help recognizing how facts connect (NRC, 2000). Articulating how an expert thinks about the connections between ideas can help students learn. For example, it is often difficult for students to grasp how genes, chromosomes, alleles, DNA, RNA, proteins, nucleotides, and amino acids relate to one another. An instructor can ask students to diagram, explain, or label relationships between these terms using a concept map (Allen and Tanner, 2003b; Novak, 2003; Morse and Jutras, 2008). The resulting maps will reveal what students are understanding, or not, and drive them to think more deeply about molecular biology rather than simply memorizing definitions. The maps are also an opportunity for students to get feedback on their thinking and for tracking how their knowledge changes as they develop an expertise.

Finally, limiting expectations to recalling facts does not give students an opportunity to learn to think at a higher level. Instructors can use Bloom's taxonomy to recognize whether students are expected to think at various levels. Specifically, Bloom's taxonomy orders levels of thinking according to their complexity (low to high): knowledge, comprehension, application, analysis, synthesis, and evaluation (Bloom *et al.*, 1956; Anderson *et al.*, 2000; Lemons and Lemons, 2013). By classifying in-class, homework, or test questions or problems by Bloom's level, instructors can develop a comprehensive picture of the amount of lower- or higher-level thinking students have to do to be successful. Crowe and colleagues (2008) have even developed a biology-specific version, called the Blooming Biology Tool. There are also assessments for testing students' conceptual knowledge (Angelo and Cross, 1993, reviewed by Sundberg, 2010; Garvin-Doxas *et al.*, 2007; Marbach-Ad *et al.*, 2010; or, search for "concept inventory" on the *LSE* website: www.lifescied.org). An improved performance on these assessments typically means understanding biology at a deeper level (but see Smith and Tanner, 2010, for caveats).

POSE MESSY PROBLEMS

Messy problems—also called open-ended, rich, ill-structured, or wicked problems—demand more than simple, factual answers. For example, in her junior-level biochemistry course for life sciences majors, the first author (E.L.D.) presents students with real data sets and scenarios to analyze and interpret, such as this one:

> A 51-year-old woman was admitted to the hospital because of sharp abdominal pain, vomiting, and fever. The patient's history was unremarkable; she had not abused alcohol and had not received any long-term treatment. A physical exam revealed that the patient was malnourished, probably due to low economic status and abdominal symptoms. Blood tests revealed anemia, iron deficiency, elevated white blood cell count, and low concentrations of total protein and albumin. During exploratory laparotomy, a fragment of necrotic cecum was identified and removed. The patient received five units of erythrocytes to treat anemia. The patient also received albumin and a high-protein diet. After 19 d of hospitalization, the woman's clinical condition improved enough for her to be discharged and convalesce at home. After 5 d, the patient was readmitted to the surgical ward with a fever and signs of wound infection. The patient was given antibiotics, and gradually her fever reduced and her wound healed. Although her general condition improved, she developed apathy, loss of appetite, and reluctance to engage in physical rehabilitation. Neurology and psychiatry services were consulted and found normal consciousness, but slow mental reactions and reduced movement. The patient had difficulty retracing a sequence of events and memorizing, and displayed disorientation with respect to time and place, slow pupil reaction to a light stimulus, and ataxia in all four limbs with near immobilization in the lower limbs. A CT scan of her brain revealed no abnormalities. Wernicke-Korsakoff syndrome was suspected, and the patient was moved to a neurological ward and her blood was tested for vitamin B1 levels, which were 9 μg/l (normal range is 33–110 μg/l).
>
> 1. Summarize the overall role or function of the pyruvate dehydrogenase (PDH) complex.
> 2. Could vitamin B_1 deficiency affect functioning of the PDH complex? Why or why not?
> 3. Summarize the overall role or function of the citric acid cycle.
> 4. Could vitamin B_1 deficiency affect functioning of the citric acid cycle? Why or why not?
> 5. The citric acid cycle is described as having "setup" and "energy harvest" phases. Which enzymes in the cycle would you characterize as having "setup" versus "energy harvest" functions? Be sure to provide a rationale for your responses.

6. What are the key regulatory step(s) in the metabolism of pyruvate?
7. Postulate as to why this patient experienced primarily neurological symptoms.

What distinguishes messy problems is that straightforward, algorithmic approaches are usually insufficient for reaching an answer. Students should be capable of solving such problems (Allen and Tanner, 2003a), but they must practice solving messy problems to transfer classroom learning to the real world (Chamany *et al.*, 2008). Messy problems are also more interesting, which makes them more motivating to solve (Ryan and Deci, 2000). Resources for teaching messy problems include the following:

- Case studies (Allchin, 2013; National Center for Case Study Teaching in Science: http://sciencecases.lib.buffalo.edu/cs),
- Problem-based learning (Klegeris *et al.*, 2013; Problem-Based Learning at the University of Delaware: www.udel.edu/inst),
- Process-oriented guided-inquiry learning (https://pogil.org),
- Course-based undergraduate research experiences (Auchincloss *et al.*, 2014; http://curenet.cns.utexas.edu), and
- Project-based applied learning (www.pal.uga.edu).

Start by copying or adapting existing problems to fit a curriculum and students. Keeping backward design in mind, start with one goal, objective, or lesson at a time: What is it that students should be able to do and how will tackling a messy problem help them learn to do it? Messy problems are challenging, so students need support, just like a child learning to ride a bike. Children start using a bike with one speed, foot brakes, and training wheels, which reduces the task's complexity while providing support. Once this skill is mastered, the training wheels come off and more complexity is added in the form of hand brakes and multiple gears. Educators call this "scaffolding" (Tanner, 2013)—providing stepping-stones to solve a complex problem by breaking it into manageable elements. Each portion is challenging enough to be interesting but not so challenging that students give up. It is important to diagnose students' knowledge and abilities before assigning a messy problem: Are training wheels needed? What would those wheels be? How could a problem be parsed into achievable steps that will ultimately help students solve the complex problem?

EXPECT STUDENTS TO TALK, WRITE, AND COLLABORATE

Students learn better by talking, writing, and collaborating (Springer *et al.*, 1999; Bangert-Drowns *et al.*, 2004; Quitadamo and Kurtz, 2007; Reynolds *et al.*, 2012; Linton *et al.*, 2014), because each requires higher-level thinking. Through these activities, students can become aware of what they do not know or understand (also known as metacognition), which ideally prompts them to think more deeply or seek more information to clarify their understanding. The process of explaining requires students to integrate new and existing knowledge (Chi *et al.*, 1994; Coleman *et al.*, 1997; Tanner, 2009). When students talk or write, they also demonstrate their skills or create products (e.g., a writing sample, a solution to a problem) that can be the basis for feedback from instructors and peers. The overall process of eliciting performance, getting feedback, and revising a performance—of either a student or an instructor—is a "learning cycle," which is a key feature of active learning. Finally, when students talk with one another or otherwise collaborate, they are more engaged and can be held accountable for their contributions, even in large classes in which students might otherwise "hide."

Talking, writing, and collaborating do not need to be complex to be effective. For example, start by asking students to respond to a conceptual question via a classroom response system ("clickers" or Web- or app-based equivalents such as Top Hat [https://tophat.com]). Then encourage students to discuss responses with their neighbors. Finally, have them revote. This approach is effective for helping students come to a more accurate understanding without any instructor intervention (Smith *et al.*, 2009). The instructor's job is to design effective questions and structure the discussion, rather than deliver information that can be learned through reading or video-recorded lectures (visit www.cwsei.ubc.ca/resources/clickers.htm for more resources and to see this in practice).

Expecting students to talk, write, and collaborate may seem daunting in courses with many students (Tanner, 2009, 2011). Students may be particularly hesitant to talk in front of hundreds of peers. Use "wait time"—ask a question and wait at least 30 s and up to a minute before speaking again—to prompt tentative students to talk, even if it is just to ask the instructor to repeat or clarify a question (Allen and Tanner, 2002). Also, allow students to make mistakes and correct them, such as the vote, discuss, revote approach. Not penalizing students for taking a risk helps them progress in the learning cycle. Using group exams (also called "two-stage exams") is another tactic. Students take an exam individually, return it, and then work in groups to retake the exam. Students' performance on the group exam has been shown to improve (Gilley and Clarkston, 2014; Rieger and Heiner, 2014), and the exam itself becomes a time to learn, as students debate scientific ideas (visit http://blogs.ubc.ca/wpvc/two-stage-exams for guidance and to see this in action).

Finally, writing assignments can be managed in courses with many students by using Calibrated Peer Review (http://cpr.molsci.ucla.edu; Pelaez, 2002; Schinske and Tanner, 2014). Students complete a writing assignment and then rate three sample assignments for content and style. Students must achieve a standard of agreement with the instructor's rating (a process called "calibration training") before evaluating the assignments of three peers and their own assignment. This strategy reduces the grading burden associated with writing tasks. It also develops students' writing and evaluation skills, while encouraging higher-level thinking. For more detailed advice about implementing these and other active-learning strategies in classes with many students, see Wood and Tanner (2012).

CONCLUSION

Like learning any new complex task, learning to teach using active learning is challenging but worthwhile. Make it easier by

1. Avoiding reinventing the wheel—many resources are already available.
2. Trying one thing at a time—perhaps start with the most comfortable thing to change or what is most fundamental yet difficult for students to learn.
3. Watching and getting feedback from instructors who are experienced with active learning—although it may be uncomfortable initially, it can be very helpful for identifying ways to integrate more active learning into a course and for getting feedback on how to teach more effectively.
4. Being transparent with students—here is an example from the first author's (E.L.D.'s) syllabus:

To be successful in this course, we encourage you to

- **Complete the assigned readings, then treat the textbook as a reference**. Do not just read the textbook over and over again—this is NOT a helpful way to study. Instead, focus on the solving the cases and problems from the assignments and class. Consider how you might alter a case or problem, and how the altered version could be solved.
- **Focus on the learning objectives**. The exams will assess your accomplishment of the learning objectives. Use the learning objectives as a guide for what to focus on when you are completing assignments and studying for exams.
- **Not spend time memorizing**. You can look up facts when you are working on assignments. Some facts (e.g., amino acid structures) will be provided for you on exams so that you can focus on applying knowledge rather than just regurgitating facts. You will come to remember the most important facts as you practice solving problems.
- Study with classmates, including working on cases and problems together. **You must submit all work in your own words**, but working with classmates will help you understand key concepts behind the cases and problems

  Education research has demonstrated that the more opportunities students have to verbalize their thinking either in writing or speaking, the more students learn. Education research has also shown that when instructors prompt students with questions, rather than giving explanations themselves, students learn more. Thus, we have designed the course to maximize your opportunities to explain your thinking to yourself, your classmates, and the instructors. There will be opportunities to solve problems in and out of class throughout the semester. By solving problems:

- You will be able to figure out what you don't know and study accordingly,
- We will be able to figure out what you don't know and tailor our instruction accordingly,
- You will be better prepared to solve problems both on exams and throughout life, especially if you pursue a career involving science or evidence-based decision making.

Active learning demands that students think at a higher level, which means they may become frustrated if they are accustomed to memorizing and recalling facts. Reassuring students that what is expected is challenging but possible builds their confidence to persist. It also helps to remind students that we also struggled with scientific problems, persisted, and benefited. Doing the real work of a discipline—designing studies, interpreting data, synthesizing literature, building and testing models, writing papers and proposals—builds skills. Trying, getting feedback, and trying again is a virtuous cycle that is consistent with decades of research on learning from cognitive science, educational psychology, and even neuroscience. Lecturing does not cause learning. Students learn by attempting a performance and then getting feedback on their performance with the aim of becoming experts. Now ask yourself, what is one action to take right now to improve your students' learning and help them to become experts?

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