Title: Seven practical strategies to add active learning to a science lecture

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Abstract

Multiple research studies have shown active learning can increase student performance, reduce fail rates, and increase the success of marginalized students in STEM. In this mini-review we discuss a simple framework for planning and implementing active learning in the classroom. We provide seven strategies to support faculty members who want to implement this framework, with five suggested teaching activities and two mechanisms of creating space in the lecture to use the activities. Each strategy is given with a foundational research paper describing the evidence that it improves learning, engagement and inclusion in the classroom. We include our own experiences using these strategies in large biology lectures that had segments devoted to neuroscience topics, but they are effective in smaller classes as well.

Key Words:

Active learning

Teaching

Education research

Discipline based education research

Biology education research

Flipped class

Underrepresented minority

Diversity

Inclusive teaching

Introduction

A number of reports have called for a change to teaching practices in large lectures in STEM (science, technology, engineering, mathematics) [1,2]. STEM degrees are associated with better economic outcomes [3], but this benefit is not equally distributed across all students. Almost 60% of all bachelor's degrees are awarded to women, but in STEM this figure is only 34% [4]. This underrepresentation in STEM, including biology, is also seen in students of color. In 2016, the US population was 17.9% Hispanic, but the percentage of STEM bachelor's degrees awarded to Hispanic students was 12.1% [5,6]. The US population is 13.4% African American, but in 2016 the percentage of STEM bachelor's degrees awarded to Black students was 8.6% [7,8]. Of all Bachelor's degrees in biological sciences awarded in 2015, only 10.5% went to Hispanic students and 7.6% went to Black students [8]. It is these disparities that lead many to suggest that improved university instruction may provide a mechanism to increase engagement and retention of women and underrepresented students in STEM.

When a change in biology teaching is recommended, the teaching practices proposed are, broadly, increased structure [9], and increased active learning [10]. High structure and active learning in a biology course require that the instructor:

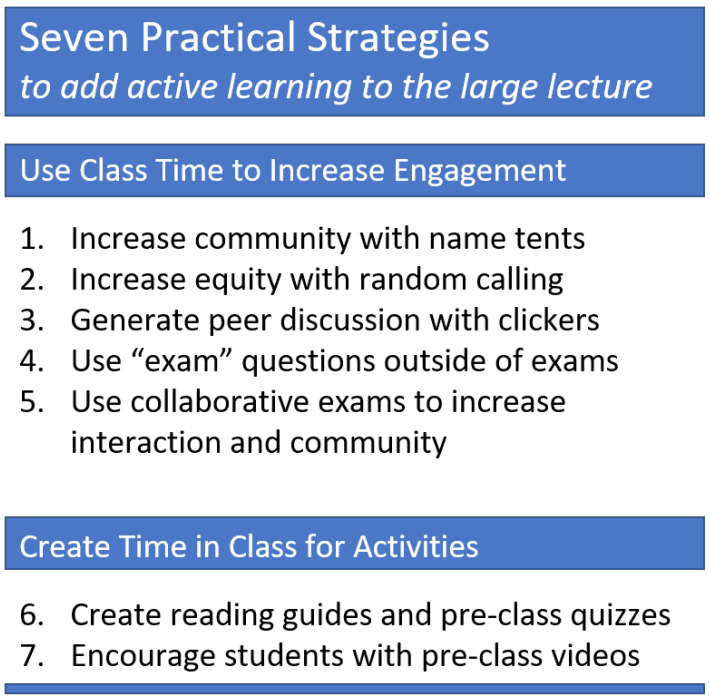
a) determine what they want students to be able to demonstrate by the end of the course,

b) determine which of those learning objectives and skills are difficult for students to master on their own,

c) develop activities to carry out during class that will give students practice in these difficult skills while in the presence of instructional staff who can motivate them and provide feedback (active learning),

d) provide a framework of content and accountability before, during and after class to maximize student engagement with the work (increased structure).

Faculty members in neuroscience have the desire to improve the success of students from disadvantaged backgrounds, but also have progressively larger classes and very high demands on their time. Being asked to "make your class more active and structured" is not a trivial request given the required steps listed above. But the good news is that even small changes in teaching can have positive effects on student learning, as we have found in our own classes [11]. For those faculty members who want to move up the spectrum of increased structure and active learning, we present a series of evidence-based techniques that range from minimal time to maximal reward (Fig. 1).



For this review, we are focusing on steps "c" and "d" in the framework above: developing the work/activities to carry out in class (active learning) and providing a mechanism of content delivery and

accountability outside of class (structure). For every example, we provide a foundational research study, a short take-home message, and a description or plan of implementation.

The tools we present are intended to be adoptable by any instructor, but all of them do require a different effort or intentionality than a traditional lecture requires. We have found this effort to be worthwhile. The increased work of preparation of new materials and strategies can be minimized by making small changes on a regular basis. We have also found that a classroom that is more engaging and active for the students is far more stimulating and interesting for us. We would never start a new experiment in the lab without first reading the literature and consulting experts, regulaly monitoring progress and modifying and/or developing strategies to achieve our research goals. We have found that investing effort in expanding and improving our teaching by building on evidence-based practices of others, continously evaluating progress, and regularly modifying our approach provides similar intellectual rewards. It also generates progress toward our goal of increased achievement and success for our diverse student body.

Step 1: Use class time to increase engagement with the material and people

After you have determined the skills that you want your students to be able to demonstrate, and you have carefully considered which of those skills are most difficult and require expert guidance, it is time to create a lecture environment that supports that guidance. It is particularly important to recognize that students vary in experience with the material, and also enter the class with different expectations of what an environment of learning looks like. Recognizing the diversity of student voices will improve the ability of each student to engage with the material. And recognizing that each of us as instructors enter the classroom with our own cultural expectations and unconscious biases can help us avoid behaviors that can prevent all voices from being evenly heard. The strength of these resources is that not only can active learning give students additional practice with course content, but it can also increase a student's sense that their presence is valued in the classroom and, more broadly, in science.

Example: Increase community with name tents

Foundation paper: Cooper, K. M., Haney, B., Krieg, A., & Brownell, S. E. (2017). What's in a name? The importance of students perceiving that an instructor knows their names in a high-enrollment biology classroom. *CBE—Life Sciences Education*, 16(1). [12]

Message: Small steps to learn student names makes a big impact on students.

Implementation and discussion:

Students who feel tentative about their skills in science often feel faceless and unimportant in a lecture hall of hundreds. Even students who find learning the material to be straightforward can find it distasteful to have all of their biology and chemistry occur in classes with no connection to other students or the instructor. The small step of telling students that their names matter will instantly demonstrate to students that you want to know who they are. One of us (Author 1) is currently using name tents in our courses (150 to 400 students) and provides students with 5x7 index cards and permanent markers to borrow. If you are in a room with very small desks, you may find it more practical to provide inexpensive conference-style nametag lanyards for students. We have students fill out the name tents on the first day of class, and have them incorporate their names when introducing themselves to their neighbor. We have to provide more name tent supplies a few weeks in when many students have managed to lose the first one. We do have to remind students to get them out, and occasionally encourage them when doing a group discussion to be sure everyone knows the names in the group.

Why we like it: We find the benefits of nametags to be similar to the benefits of active learning activities in microcosm. Some students embrace the idea, while others sigh heavily and do not seem motivated to use theirs. But we find that the ability to talk to students and refer to them by name reduces a significant barrier to interaction. Perhaps even more importantly it provides a mechanism for students to introduce themselves to each other and to continue conversations from lecture to lecture. Without this prompt, some students would chose not to engage rather than admit they do not remember the name of the person they met previously. We tell students they are welcome to add their pronouns to their name tents, which can make the classroom environment more comfortable for LGBTQA+ students who wish to identify this

information. We have also asked students to provide phonetic spelling so we can pronounce their name correctly. Because these name tents or tags are portable, we or the teaching assistants can require them in discussions or labs as well. All these actions reinforce the message that even though there are many students in this class, each of them is unique and important.

Additional reading: Cash et al., 2017 [13]

Example: Increase equity with random calling

Foundation paper: Eddy, S. L., Brownell, S. E., & Wenderoth, M. P. (2014). Gender gaps in achievement and participation in multiple introductory biology classrooms. *CBE—Life Sciences Education*, 13(3). [14]

Message: Instructors can overcome unconscious implicit biases with simple changes.

Implementation and discussion:

Many instructors value asking questions to the class during their lecture as a method of engaging students. However, it is important to be aware that there are students in the class who will never volunteer to answer because they are nervous about speaking in a large class or afraid of being wrong. Importantly, studies show that people who do not volunteer are more likely to be women and people of color [9, 15]. Even more interesting is the unconscious bias that may occur when instructors *choose* students to answer a question [16, 17].

Unconscious bias is difficult to accept because we all want to be fair and supportive of all students. But because research indicates that we all have unconscious thinking and behaviors, we cannot assume that intention and effort is sufficient to make us equitable teachers. If you do want to call on students, it is therefore helpful to have practices in place that generate increased equity, and random calling is a good example of a simple strategy that increases the variety of voices in the classroom. Random calling can be easily implemented in any size classroom or lecture hall. Instead of asking the class a question and waiting for someone to raise their hand (which often produces male and ethnic majority volunteers), make it clear that you will randomly call on students in this class. Create a list of student names (and survey

students to get pronunciation early in the term), and randomly sort the list each day. You can sample without replacement each day, so students who have answered once know they won't be called on again. Because random calling can be very stressful for students, particularly in large classes, we recommend these strategies to faculty members who normally ask students to volunteer answers in lecture.

- Think carefully about your philosophy of asking questions of the class. What is your goal in doing so? Are there other ways you can engage students that are less anxiety-producing and increase the participation of everyone?
- Reduce the number of questions you are going to ask students to answer. For easy questions, we ask everyone to shout out the answer, engaging the entire room. For questions with a binary choice (afferent or efferent, higher or lower) we take a quick vote by raised hand - engaging everyone.
- For difficult questions, we first ask it as a clicker question and encourage students to discuss the question with their neighbors or small group, and then click in. Afterward, when we randomly call on a student, we ask them, "what did your group think was the correct answer?" which lessens the student's fear of being wrong because the group shares the blame.
- Tell students they are allowed to "pass," or to ask a clarifying question instead of providing an answer.

Why we like it: Neither of us tends to ask for student volunteers to answers during lecture, so we implement random call less than other techniques. The first author often asks students for shout-out answers (above) or uses group clicker responses, moving among groups to ask about answers. The second author has used small group work followed by random call using a jar of cardboard tags with seat numbers. When we visit classes where the instructor regularly requests student volunteers to answer questions, we encourage them to consider group work and random call instead. By maximizing involvement by all students in every question asked, it encourages everyone in the classroom to work through the problems, use the vocabulary of neuroscience, and get feedback from their neighbors.

Additional reading: Grunspan et al., 2016 [15]

The remaining examples presented in this section require time in class to implement. We will cover how to carve out that time in the next section, but for now imagine that the instructor has at least five to ten minutes available to carry out small group work, and has a mechanism available to collect student work.

Example: Generate peer discussion with clickers

Foundation paper: Smith, M. K., Wood, W. B., Adams, W. K., Wieman, C., Knight, J. K., Guild, N., & Su, T. T. (2009). Why peer discussion improves student performance on in-class concept questions. *Science*, 323(5910). [18]

Message: Peer discussion enhances learning, even when none of the group originally understood the topic.

Implementation and discussion:

Most faculty members are familiar with clickers, and many use them in their large lectures. But using clickers to their maximal effectiveness is not intuitive. Some faculty members use clickers as an attendance tool, while others ask very simple questions after each concept, which rarely generates interest or energy from students. Often faculty members say they do not know how to organize a more complex activity using clickers and questions to generate discussion. Below we present a short overview of a simple but high-quality clicker activity that incorporates student discussion.

- First, use difficult questions relevant to the current lecture topic, and if these can be identified as questions from previous exams this helps get the students' attention. The best questions have common misconceptions as the wrong answers, so students are really unsure what the correct answer is and are motivated to find out. Have students first answer the question on their own with clickers, but do not show them the histogram of responses or tell them the right answer.
- Second, generate peer discussion. With good clicker questions, students sitting near each other likely chose different answers. You can see (before revealing to students) that a question had many incorrect answers chosen, and can encourage students to discuss the best answer with a

neighbor. It can be helpful at this point to walk around the room and ask students privately why they chose different answers. After the discussion, have the students re-vote to see if understanding improves. Refrain again from showing the clicker-generated histogram.

- Third, give an explanation of the answers. A good question has created interest and student engagement. Multiple answers seemed reasonable, and students want an explanation of why the right answer is right and why the wrong answers are wrong. Your explanation should combine this student interest with content clarification. If you are particularly dramatic you can explain all the wrong answers until only the right answer and the most popular wrong answer are left, and then produce a big reveal, generating a big response of joy or disappointment from the students.

Why we like it: We have found the most powerful time of using a difficult clicker question is that moment after students have voted but before we reveal the answer. Students are poised to find out if they were correct - they argued for their answer with their neighbor and discussed why the wrong answers seemed wrong. At that moment they are *interested* in the topic and are ready to hear more.

Additional reading: Smith and Wood, 2011 [19]

Example: Use "exam" multiple-choice questions outside of exams

Foundation paper: Nicol, D. (2007). E-assessment by design: using multiple-choice tests to good effect. *Journal of Further and Higher Education*, 31(1), 53-64. [20]

Message: Good classroom activities use something students care deeply about (and you already have available).

Implementation and discussion:

Perhaps a faculty member is perfectly willing to try active learning, but has no idea how to create an activity other than clicker questions. One activity that is easy to implement is to create a small-group discussion around old multiple-choice exam questions. This is useful to students because they often do not spend much time carefully thinking through these questions during an exam. A solid implementation

for creating an activity around an old exam question follows a template we use for all our active learning activities: craft, sell, collect a product, debrief.

- Crafting an activity requires the instructor to plan something difficult enough that students will need to give it attention and focus, but not so difficult that they see no way to make progress on the problem. An old exam question fits this requirement, but it is important to pick an old exam question that will stand up to student attention. It should match the learning goal of the lecture, have reasonable difficulty (30-75% correct), and show good discrimination (students who answered correctly did well on that exam overall). Ideally, the question should have incorrect responses that are common student misconceptions.

  A good activity to use with an old exam question is simply to present the question on a slide, and tell students, "This is an exam question I gave students in a past term. For the next ten minutes, I want your group to write a response to each option on this multiple choice exam question. Explain why each incorrect option is wrong, and why the correct option is correct. You will turn in your response in ten minutes, and then I will explain my reasoning when I wrote the question." As students work on this project, the instructor (and TAs or LAs if present) can circulate and listen, and be available to answer student questions. This time is often illuminating for instructors, as it may be the first time they hear a student describe why they have chosen or discounted a question option on one of their exam questions.
- Selling an activity means explaining to the students why it will be beneficial to them to complete the activity. If a student believes that working hard on something will provide a clear benefit, they are more likely to participate and discuss the activity with neighboring students. Studying an old exam question written by the instructor is an easy sell, because students are motivated to answer future exam questions correctly.
- Collecting a product is a critical step that we often see instructors skip because of the perceived effort involved. Collecting the student's work has two main benefits. First, it forces the instructor to think about what the collected product should look like, which causes them to give clearer

instructions and improves both the sell and the engagement of the students. Second, students who know they will have to turn in their responses before hearing the answer will recognize that they need to put in the work and cannot just sit quietly or chat and wait for the instructor to provide the answers.

For this activity, the instructor can collect the responses using an analog tool or a digital tool. A simple analog tool is index cards, which students can bring to class or can be handed out by the instructor. Students can write the answer on one side and student names or IDs on the reverse. Index cards are easy to sort and quick to check them off for participation by the instructor or TA. The benefits to index cards are that their size limits the student response, and in rooms with a document camera the instructor can display several cards anonymously and discuss best responses.

Digital collection, such as having students type their responses into an assignment in their learning management system (LMS) in class, can also work well. It automatically associates the response with a student for grading, and collects and stores the responses without the need for paper. In many LMSs, the instructor can hide student names and show several responses to the class using their own login to the LMS as soon as they are received.

- Debriefing is an important step for both the instructor and the students. Working on an exam question may expose misconceptions about the topic being studied. Students are also motivated to hear if their logic was correct for why answer choices were right or wrong. They will often ask questions to get clarification on why their logic wasn't supported. The instructor may realize at this point that students have valid reasons for discounting an option intended to be the correct answer, or for choosing an option that was incorrect.

Why we like it: We have found this activity benefits both the students and us as instructors. Focusing on an exam question is often a great summary of a topic we have just discussed, and students tend to be engaged and interested. Exposure to sample exam questions provides studenets feedback on their level of

preparation [21]. This activity has also improved our ability to write effective exam questions because we get regular feedback about how students interpret our questions.

Additional reading: Tanner, 2013. [22]

Example: Collaborative exams increase interaction and community

Foundation paper: Jang, H., Lasry, N., Miller, K., & Mazur, E. (2017). Collaborative exams: cheating? Or learning? *American Journal of Physics*, 85(3), 223-227. [23]

Message: Change exams from isolating endeavors to community-building experiences.

Implementation and discussion:

Collaborative or "two stage" exams are a technique that can be used for either small quizzes or large, summative exams. The main idea is that students take an exam twice - once on their own, and then again, immediately, as small groups. Their final exam score is some combination of the two exam scores. This activity works best on exams that have fewer but difficult questions. The basic format of a collaborative exam is as follows:

- The instructor passes out the exam to each student, and each student works on their own to complete the problems. The exam is submitted to the instructor. The majority of exam time is given to the individual stage (up to 3/4 of exam time), but the exam itself will need to not take the full time period. The majority of the exam score (often 85 - 90%) comes from the individual score, so students are not tempted to reduce their study time.
- While individual exams are handed in, students move themselves into predetermined groups of 3 or 4. A second exam of the same (or very similar) questions is handed out to students. Students in each group turn in a single answer sheet, so they must come to consensus in the time available. The group exam time is packed with conversations about the question and students are motivated and focused to understand the concepts involved.

Why we like it: We have not yet used this strategy for high-stakes exams, but have used it regularly in discussion sections and have seen very strong engagement by students. Energy in the room is high and the

conversations about biology are on topic. Our regular course times are 50 minutes, which is tight for a two-stage exam, but we hope to implement it in the near future in introductory biology.

Additional reading (including benefit to marginalized students): Roberts et al., 2018 [24]

Step 2: Create Time in Class

Now that we have outlined the kinds of activities that are possible when we take a break from lecture, we can discuss evidence-based methods to move lecture content out of classroom. In our own teaching, we have used different techniques to do this, and for different amounts of class material. One of us (Author 2) has used both reading guides and short "screencast" videos that move 5-10 minutes of lecture content to work that is done pre-class. The reading is followed by online quizzes. This shift provides time for a single in-depth activity during class. Alternatively, one of us (Author 1) fully "flipped" the same introductory biology class, preparing screencast videos and online quizzes for the all the course content, allowing all class time to be used for problem solving and discussion of scientific research. In each of our iterations, class size was over 400 students. Whether small amounts or large amounts of content are moved outside of the classroom, time is now available during class that can be used for an organized activity like the ones described in the previous section. Below we provide options for how to move this content outside of class.

Example: Create reading guides and pre-class quizzes

Foundation paper: Heiner, C. E., Banet, A. I., & Wieman, C. (2014). Preparing students for class: How to get 80% of students reading the textbook before class. *American Journal of Physics*, 82(10), 989-996. [25]

Message: A focused reading guide and pre-class quiz will greatly increase the number of students who read the textbook.

Implementation and discussion:

Most instructors would likely be willing to remove the introductory concepts or vocabulary that they cover in a lecture if this material is covered clearly in the textbook. But instructors are stymied by the unwillingness of students to do the assigned reading before class, so they feel they need to spend the class time teaching material that students could easily teach themselves. This creates a negative cycle where students do not need to do the reading because the instructor covers all the necessary material in class. We have found it is relatively straightforward to motivate students to do pre-class work and come to class familiar with the basics of the lecture. Here is advice we offer:

- Provide very clear guidance to students about what you want them to learn before class. It is not sufficient to give students a chapter, or even a chapter section, particularly if you normally write tests based on your lecture notes. Instead, provide a reading guide with questions students should answer from the reading. You can also focus a reading guide around figures in the text, and list questions about the experiment or principle for students to answer. Make sure this is content that is clearly related to exam questions. Help students feel confident that they have captured exactly what they need to know for class and exams.
- Make the pre-class work short and straightforward. Ideally, the reading and quiz should take an hour or less, and should be vocabulary and introductory material. The first time we used these we had undergraduate students in our lab at similar levels do the exercise and report the time needed to complete it. This information was used to provide an estimate for time that was noted at the beginning of each pre-class activity. Students are more likely to do work that they know they can accomplish the night before each class. Think also about notetaking, and whether you can provide blank diagrams for students to fill in. Ideally, the pre-class reading will generate student notes like lecture notes that they can use for study.
- Provide accountability with an assignment or quiz. An online quiz is common, but you can also request students to summarize what they've learned in an online writing assignment. The assignment should be worth a small amount of points. Answer sharing between friends can be reduced by question randomizing. The goal here is to provide the motivation to do the work, so

the quiz should be basic enough that anyone who has taken notes on the reading can receive full credit.

- Do not cover that material in class. If it is clear to a student that you are assuming they have done the reading and know the basics, they are more likely to do the reading and know the basics. We know instructors who use the effective technique of keeping their old introductory slides in their slide deck but with a different background color, and deliberately clicking past the slides at the start of class, saying, "here is the material you have already learned," before starting the lecture with the more advanced material. This reinforces to students that the pre-class reading is required and important (and will be tested).

Why we like it: It was initially difficult for us to believe that we could completely let go of lecturing on very important biological concepts. We measured the effect of pre-class preparation in our own class [11] and found that extra activities in class on more difficult concepts improved student performance on exams compared to when we lectured on the material.

Example: Encourage students with pre-class videos

Foundation paper: Stockwell, B. R., Stockwell, M. S., Cennamo, M., & Jiang, E. (2015). Blended learning improves science education. *Cell*, 162(5), 933-936. [26]

Message: Creating videos as pre-class assignments can improve student interest and exam scores compared to text-based pre-class assignments.

Implementation and discussion:

Creating pre-class reading guides is an effective tool to prepare students for active learning in class. But if an instructor finds that the textbook is not an ideal source, making simple pre-class videos can be even more effective. Designing a video can provide a precise focus on content important to you, and can increase the connection students feel with you that the text does not provide. It has been our experience that making videos does not need to be overwhelming if approached with clear boundaries. We recommend:

- Create a video if you want students to understand a more difficult concept. Reading guides for basic content are generally accepted by students, but if they need to learn about a complex topic before class, they find it helpful to hear their instructor explain the information with accompanying visuals.
- Add only a few videos per term. Unless there is a sudden worldwide pandemic, you do not need to have all your course content as immediately available as videos. A colleague of ours decided to first only make pre-class videos for her Friday classes ("Flipped Friday"), which reduced the workload.
- Videos do not need to look professional. You do not need to edit out your "ums" or pauses. We find students would rather have three helpful-but-imperfect videos than one high-quality video. One practice run-through can reveal gaps in your planned explanations that should be fixed before recording, but do not practice multiple times.
- Simple screen capture software and a mouse is generally sufficient. You do not need to get the 'premier" version of software or a digital tablet. If you want to handwrite or draw, you can rig your phone to be above a pad of paper and record your writing using your phone. Contact your campus teaching center to ask for recommended software.
- Speak at your normal pace and move quickly through the content. Students can slow or re-watch a video if they need to, and brisk videos are more engaging to watch.
- Do not videotape slides with lots of text. Have the text as your notes, and instead show the relevant image, or your face.
- Give students notetaking instructions for your videos. Not all students will recognize that you intend your video to be content that needs to be captured and studied, just like lecture with its lecture notes. Provide guiding questions, or a notetaking sheet with matching images, to remind your students that they will be held accountable for the material.

Why we like it: There are many concepts in biology that benefit from visuals and animations, that are difficult to reproduce in a textbook. Using videos has allowed us to create short, solid "lectures" about

concepts that used to take up class time. Students like being able to re-watch the videos, and students for whom English is not their first language find captions that go with the video to be extremely helpful. With content moved outside of class time, we are able to create engaging activities that get students closer to the work of actual scientists - reading figures, solving problems, and designing experiments.

Additional resources: Brame 2016 [27]

Conclusion

Often faculty members are interested in making their classes more active and inclusive, but aren't sure how to efficiently make changes with the limited time they have available. In this short review, we have presented evidence-based techniques to make space for active learning and then implement it. Some techniques require a significant amount of time to implement, but others are very quick to use. It is our view that to be effective the science education environment should be as dynamic, intellectually stimulating, and evaluative as the scientific research enviroment. Therefore, the time we spend updating our classes will benefit us as well as our students.

We have intended this to be a standalone article with sufficient details to implement the techniques, but each of our recommendations comes with a full history of research and resources. Faculty members who wish to learn more about evidence-based teaching in the biological sciences are encouraged to explore the following:

- CBE-Life Science Education (Journal): https://www.lifescied.org/
- SABER (Society for the Advancement of Biology Education Research): https://saberbio.org/
- The books Small Teaching and Small Teaching Online for additional ideas for small changes to increase student engagement in the college classroom [28, 29]
- The book Teaching and Learning STEM, for a more thorough, step-by-step guide to incorporating active learning in STEM classes [30].

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