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Review

Active Learning: Developing Self-Directed Learners Through Strong Intellectual Engagement

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Abstract

When they were students, many current science instructors learned through traditional lectures. This mode of passive knowledge transmission has been shown to be less effective for student learning than an approach that involves students in a more active and engaged role in their learning. Without first-hand experiences with active learning, current instructors face challenges as they try to incorporate active learning experiences into their classrooms. In this review, we summarize the field of active learning, including relevant pedagogical philosophy and features of commonly used activities. We end with future considerations that could help disseminate and improve the implementation of active learning in college science classes.

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INTRODUCTION

During learning, the brain is hardly dormant. At the molecular level, neurons in the brain produce and degrade more than a hundred different proteins within four hours after learning (1). There is a stark contrast between the dynamic movements of the molecules and signals needed for learning and the traditional classroom, where students sit passively listening to the lecturer.

For many years, educators in the fields of science, technology, engineering, and mathematics (STEM) have been campaigning for a change in teaching methods to reinvigorate the science classroom (2-4). The term active learning has emerged as a key ingredient of recent science education reform, which seeks to equip instructors with new educational tools and improve the way students learn. Over the last few decades, active learning has become a central topic in the educational literature (Figure 1). In 2016, PubMed alone cataloged roughly 265 publications on active learning. This increase in educational research resulted in the expansion of active learning strategies in different fields of education, as well as more rigorous analysis of the effectiveness of active learning techniques on student learning.

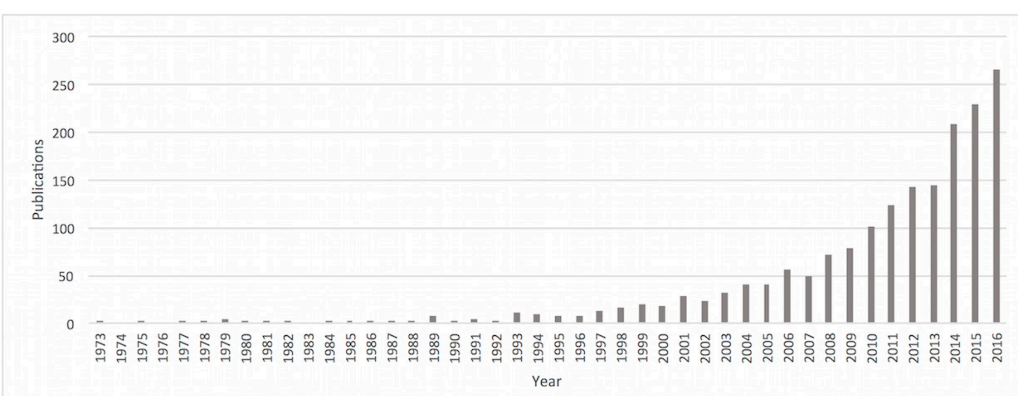

Figure 1. The number of annual publications that contained the phrase "active learning" in PubMed from 1973–2016. The values were extracted from the Medline (PubMed) Trend website (http://dan.corlan.net/medline-trend.html).

In this review, we aim to provide science instructors, who may not be versed in active learning, with a concise introduction to active learning interventions. This introduction will include the definition of active learning as well as its educational context, features, and effectiveness. We also include a list of active learning interventions and web-based resources, and conclude with a brief discussion of future directions in the field. We direct readers who are interested in specific active learning interventions to other recent comprehensive reports (for example, see 2, 5-10).

What is active learning?

There are numerous explanations and definitions of the term "active learning" in the educational literature as well as in non-professional contexts. Each definition differs slightly from others. Arguably one of the best lexical definitions of active learning was suggested by Collins and O'Brien (11):

> "[Active learning is] The process of having students engage in some activity that forces them to reflect upon ideas and how they are using those ideas. Requiring students to regularly assess their own degree of understanding and skill at handling concepts or problems in a particular discipline. The attainment of knowledge by participating or contributing. The process of keeping students mentally, and often physically, active in their learning through activities that involve them in gathering information, thinking, and problem solving."

The quote above explicitly demonstrates a key component of active learning - active mental engagement. What is implicit in the quote is that active learning encourages students to own their learning, the second component of active learning (12) (Figure 2).

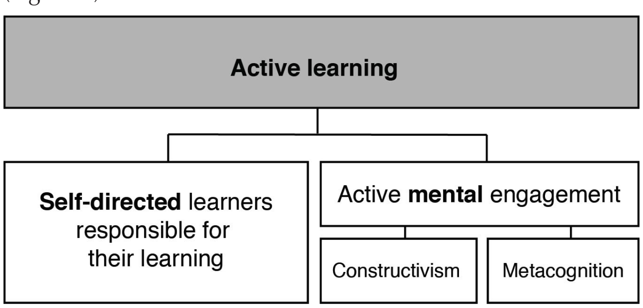

Figure 2. Two dimensions of active learning. Active learning imparts a sense of autonomy to students, causing them to feel an ownership over their own learning. Additionally, high quality active learning incorporates high-level Bloom's taxonomy in the exercises, engaging students in both constructivism and metacognition.

Two pillars of active learning: self-directed and active mental engagement

Instead of being passive learners, students in an active learning setting are prompted to become responsible for their own learning (12-13). Self-directed learning, sometimes also referred to as flexible learning in the literature (14), emphasizes a focus on the students and learning, as opposed to the teacher and teaching. Phrases often used to describe this concept are "teaching more by talking less" (15) and "show, don't teach" (16). To motivate students to follow their own curiosity and take ownership of their learning, some active learning interventions ask students to formulate their own hypotheses, design experiments, and solve open-ended problems (17-20).

In general, descriptions of active learning contain verbs that describe student action, indicating that active learning interventions entail meaningful, hands-on/minds-on activities designed to invite students to think about what they are learning (10,21-22). Active learning requires strong intellectual involvement through higher-order thinking. When the learning objectives require complex cognitive tasks such as application, evaluation, and synthesis of knowledge (23-24) (Figure 3), students benefit from active learning interventions inherently designed to elicit strong intellectual involvement.

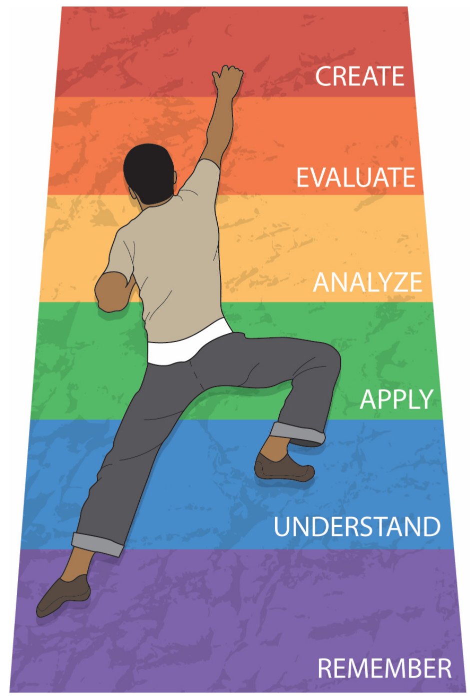

Figure 3. Active learning is at its best when engaging higher order levels in Bloom's taxonomy. Each level of Bloom's taxonomy (23-24) has accompanying verbs that describe assessment types: remember (e.g., define, describe, identify), understand (e.g., distinguish, predict, review), apply (e.g., illustrate, manipulate, solve), analyze (e.g., compare, discriminate, examine), evaluate (e.g., argue, explain, interpret), create (e.g., design, devise, simulate). A 3-dimensional representation that conveys the intersection of knowledge and cognitive aspects of the revised Bloom's taxonomy can be found here: http://www.celt.iastate.edu/wp-content/uploads/2015/09/RevisedBloomsHandout-1.pdf.

It is important to note that these two elements of active learning - self-directed learning and strong intellectual engagement - are independent from each other. For example, an active learning intervention may ask students to simply recall factual knowledge (low on the Bloom's scale). Conversely, critical thinking can also be prompted in a traditional lecture setting (12,25-26). Therefore, when designing active learning interventions, educators should keep in mind that active learning interventions need to promote both student autonomy and deep thinking (12).

How can one elicit active intellectual engagement?

For the last few decades, teachers and educators have been emphasizing the need to better facilitate learning in their students. Over this time, two main concepts have emerged and been refined to form the cornerstones of fostering active intellectual engagement in students.

Encourage students to construct their own knowledge and incorporate new knowledge into an existing framework

The classical way of teaching, often referred to as the empty vessel model or objectivism, sees the instructor standing in front of the class telling the students about a certain topic (27-28). The teacher is simply transferring information, expecting the students to absorb and replicate the knowledge. In contrast, constructivists deny the notion that knowledge can be mechanically transferred to and replicated in a learner (27,29). Instead, constructivists consider learning to be a process in which students construct the knowledge for themselves (29-33). In this model, the teacher becomes a "knowledge facilitator," who aims to create an environment in which constructive learning can happen (Figure 4).

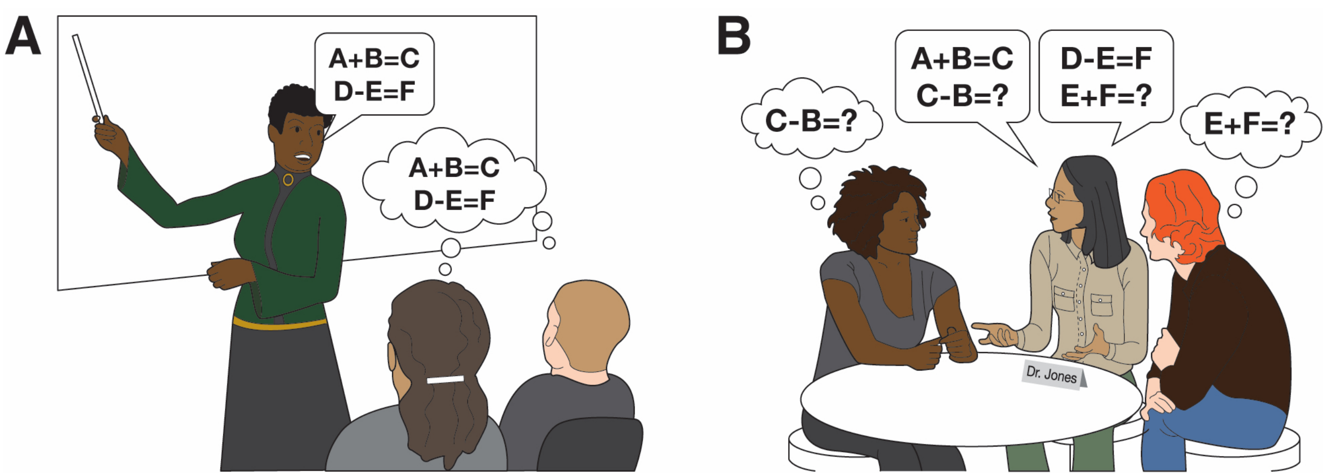

Figure 4. Constructivism changes the role of the instructor. (A) Traditionally instructors transmit information to students as a "sage on the stage" (34). (B) Constructivism aims for students to construct the knowledge by themselves, with the instructor acting more as a "guide on the side" (34).

Studies directly comparing traditional versus constructivist teaching found that constructivist teaching leads to an increase in student engagement and greater learning as measured by test scores (35-36). Interestingly, some of history's greatest scientists and teachers already understood the importance of having students construct their own knowledge. For example, Albert Einstein has been quoted as saying *"I never teach my pupils; I only attempt to provide the conditions in which they can learn"* (http://www.quotationspage.com/quote/40486.html).

A characteristic of constructivist teaching is to compare and contrast new information to pre-exiting knowledge. Learning does not happen in a vacuum. Instead, learners create an internal interpretation of new information based on their prior experiences. One illustration of this idea is a scene from Antoine de Saint Exupéry's *The Little Prince*, in which a drawing can be interpreted either as a hat or as a boa constrictor digesting an elephant, depending on the interpreter and his/her prior experience. In a recent study that examined the effect of pre-existing background knowledge on learning of vocabulary and comprehension skills in pre-school children, students with existing background knowledge performed better in a given task than those without that knowledge (37). The researchers also showed there are no differences between the two groups when the task was unrelated to particular prior knowledge (37).

As a result of the impact of existing knowledge on learning, the process of true learning often must resolve conflicts between previous understanding and new ideas (a concept referred to as cognitive dissonance) and the subsequent assimilation of new knowledge (38-39). Educators can induce cognitive dissonance by challenging students to critically evaluate their existing knowledge and address misconceptions (40). Furthermore, using real-life questions and scenarios in active learning interventions can create the context to which students can link new concepts. A study using instructor-generated "pseudo peer" diagrams to elicit cognitive dissonance in first year engineering students, found that students using these models were more likely to notice key features and identify misconceptions in their own work (41). Identifying cognitive dissonance can also motivate students to evaluate previous knowledge more critically and be open to potentially changing their existing framework.

Reflect on the progress of one's own learning

Challenging students' prior knowledge and aiming for higher-order thinking through application of the acquired knowledge are part of metacognition, the continuous reflection on the ongoing learning progress. John Flavell, a pioneer of the work in this field, defined metacognition as "one's knowledge concerning one's own cognitive processes and products or anything related to them" (42). In other words, students need to have knowledge of their cognitive abilities (i.e., knowledge about the learners themselves as well as their learning strategies) and the need to be able to monitor their learning process (i.e., ability to plan and predict, evaluate and assess) (43-44). Studies have suggested that high metacognitive skills promote effective structuring and evaluation of one's knowledge, which are necessary for academic and cognitive achievement (43,45-46).

Students benefit most from this metacognitive process only when it is guided. While enrolled in a course, students are constantly exposed to course material through lectures, office hours, assignments, etc. This persistent exposure can evoke a false sense of knowledge. For example, when people are asked to retrieve a memory, they partially rely on a "feeling of knowing" and tend to be overconfident about their recollection (47-49). In a recent study, researchers gave participants an easy test about North American geography with the intent to enhance participants' self-perceived expertise in the subject. These participants were more likely to claim knowledge of nonexistent places (e.g., Cashmere in Oregon) than another group of participants who were given a more difficult test (50). In addition to overestimating what they know, students often confuse factual surface knowledge with deep understanding, a phenomenon sometimes referred to as the illusion of explanatory depth (51-52). This false sense of knowledge is even worse than lack of knowledge since the students do not realize that they are missing crucial details.

Therefore, incorporating frequent assessments of both the lecture material and the students' metacognitive processes as part of the instructional routine can enhance student learning. Other ways of helping students monitor their own learning progress include outlining goals and objectives, providing practice questions for students to test their knowledge, giving writing assignments that prompt students to reflect the lecture material or exams, and using peer review / peer learning (e.g., students teaching each other, small group assignments, etc.) (53-56).

Active learning strategies

Features of active learning interventions

Active learning strategies that are widely used in STEM courses have different formats, but they share some common characteristics (Table 1).

First, all active learning interventions elicit active engagement of all students with the course material. This engagement is especially important in large instructor-led courses in which only a very small number of students could otherwise participate (e.g., by answering the occasional questions posed to the group by the instructor). Activities involving clickers or peer discussions have been shown to be inclusive of a more diverse set of learners and increase student learning as well as overall participation (35,57-58).

Second, active learning interventions often encourage students to explain their knowledge and reasoning to themselves or peers. The positive effect of explanation on learning has been well documented (59). In particular, explanation helps the learner apply newly acquired concepts to novel situations (60-63). A study done in an undergraduate genetics course revealed that peer discussion improves student learning by gains in conceptual understanding, not by simple influence of peers (64).

Third, some of the active learning interventions facilitate two-way communication between students and the instructor. Many in-class active learning interventions provide the medium through which instructors directly learn about their students' level of understanding. Indeed, active learning interventions have a component of assessment (65) in them. This immediate feedback allows instructors to respond and adjust their teaching based on student understanding.

Fourth, active learning interventions often include homework assignments that require higher-order thinking than was practiced in class (23-24), asking students to apply knowledge, analyze data, generate new ideas, etc. These assignments not only compel students to delve deeper into the material, but ideally can also tap into student creativity.

Evidence for effectiveness of active learning

A recent meta-analysis of 225 studies that tested the effect of active learning in undergraduate STEM education showed that active learning resulted in higher exam scores and lower failure rates than traditional lecturing (66). Other studies with randomized control groups and more rigorous experimental regimens strengthen the conclusion that active learning improves learning for all students (67-69).

A study in a physiology course showed that, in a traditional lecture course, students with little science background usually performed worse than students who had a stronger science background. However, after active learning was incorporated into the course, all students showed a benefit. Additionally, the students with little science background performed as well as those who entered with a stronger science background (70). Therefore, active learning can provide more equitable opportunities for less prepared students to learn, thus mitigating the effects of unequal access to high quality science courses in high school, for example.

Active learning, while beneficial for all students, also helps reduce the disparity in academic performance (i.e., the achievement gap) between different subpopulations of students. Haak et al. (71) showed that the incorporation of active learning via higher-order assignments (i.e., problem-solving and data analysis practices) in an introductory biology course improved the performances of all students, reducing the achievement gap between students from disadvantaged and non-disadvantaged backgrounds. However, the study further demonstrated that different student subpopulations benefit from active learning interventions differently depending on their personal and cultural backgrounds (71-73). By providing students with additional learning strategies, active learning classroom accommodate diverse student learning preferences (74).

In addition to enhancing academic outcomes, active learning also leads to changes in student study behaviors and perception. After the addition of active learning into an introductory STEM course, students reported that they spent more time studying for the course and were more likely to complete and appreciate the pre-lecture assignments (72). Other studies found that in-class active learning interventions increased participation by generating an environment of confidence and comfort (58), while enhancing the performance of underrepresented minority students (75).

Considerations and trade-offs when using active learning

A study with introductory biology classes published in 2011 (40) was a surprise to many in the STEM education community. The data showed that active learning interventions did not result in learning gains as previous studies have reported. The authors speculated that without rich pedagogical knowledge, the instructors did not use active learning interventions effectively (40). For instance, adding in-class exercises without reducing the lecture material could make the delivery of lectures cursory and shallow, which is the opposite of the purpose of active learning. Moreover, active learning interventions could be viewed as distractions when cognitive skills required in the exercises are not aligned with the skills that other assessments in class aim to develop.

Arguably the biggest cost when incorporating active learning is class time. Given that class time is limited, spending it on active learning interventions usually results in less coverage of material via lecture. Instructors can still expect students to cover all of the material, for example by providing study guides, practice tests, and reading assignments, and by assigning the tutorials available with their text. Additionally, when preparing for lectures or assignments with active learning elements, instructors have to invest significant time in identifying learning goals and designing questions and activities that engage students with the material beyond factual recall. (A good strategy is for the instructor to take the "punchline" from the lecture that they planned to present and turn it into one or more questions. For example, instead of explaining a graph, ask students to explain it.)

Some active learning interventions might (or are specifically designed to) take students out of their comfort zone. For instance, some active learning interventions force students to speak up in class and thus may alienate introverts who prefer quiet introspection. Certain active learning interventions might be inappropriate if the class contains students with disabilities or special needs. Therefore, some students might not appreciate these activities and instead prefer a more passive lecture. Furthermore, much like deciding the level of detail to pitch a traditional lecture, the level of required thinking for the active learning intervention could be too challenging or not challenging enough for a subpopulation of students in the class.

Active learning resources

Table 2 contains a selection of websites, including learning centers affiliated with universities, that are valuable resources for active learning interventions. This list is not meant to be all inclusive. We encourage readers to share their favorite resources using the "comments" tab on the article.

What do students think about active learning?

Surveys that explore student feedback on active learning found that the majority of students generally like active learning interventions and consider them as important tools for their academic performance (70,76-79). Interestingly, Welsh et al. (79) found significant differences by gender (with female students rating the active learning interventions more important than male students) and by year (upperclassmen rating the active learning interventions less important than first/second year students). Students report that they enjoy classes that use in class active learning more than traditional lectures (70). The authors of one study concluded that clicker questions seem to stimulate internal motivation by generating an interesting and engaging lecture environment (80). Students viewed clicker questions during lecture as a helpful way to reveal misconceptions and to give feedback to the instructor if the majority of the class did not understand a certain concept (79). Students also reported that instructors were more likely to go over challenging concepts again when seeing quantitative data of how many students did not understand the concepts rather than after asking the class "Who did not understand this?" (79).

In surveys regarding students' perspective of active learning, negative comments fell into three major categories: the activities wasted time; the questions were too easy or too hard; and the effectiveness of group discussions depended on the engagement of their fellow students (79). A recent study with medical students showed that, while the students were supportive of the general concept of active learning, they also expressed frustration about perceived inefficiencies (81).

Future directions

Education research has collected convincing evidence for the benefits of active learning in different fields and student populations. Education researchers are now shifting their attention from asking if active learning works to how it works. Below, we briefly list some future considerations in the growing field of active learning, as well as a recent trend that may shape the landscape of higher education and demand revision of the current structure of active learning.

Future research on active learning

Freeman et al. (66) concluded their meta-analysis of active learning studies by proposing "second-generation research" on active learning. The focus of these future studies should be identifying attributes that significantly contribute to the positive outcome in active learning, such as the types of questions and the degree of student collaboration. Future studies should also compare different types of active learning interventions and determine the optimal settings in which active learning can lead to the best learning outcome (8).

The need for clearer understanding of how active learning interventions work is also apparent from a study that investigated 33 randomly-chosen college biology courses. The authors found that the frequency of active learning interventions is not correlated with student learning and cautioned that wrong implementation of active learning could nullify its potential to have a positive effect (40). To properly train educators in active learning pedagogy, the science education community needs to establish a "certified" tool box of active learning interventions and guidelines that enable easy adaption of the strategy to different fields and contexts. Detailed descriptions (e.g., which types of question work best in which student group) and "troubleshooting" suggestions will allow other teachers to adapt and improve new exercises.

The use of active learning within a course has been shown to increase long-term retention and deep learning (82-83). However, most studies focus on the use of one specific pedagogical tool and assess learning at the conclusion of the course or just few months later (84). Future studies should look at whether and how the use of active learning interventions make a difference in long term retention (e.g., 3-5 years) of information and/or skills, as well as engagement and persistence in STEM majors.

Most existing active learning interventions were designed to enhance student understanding of specific concepts introduced in class. Addressing the overall goal of higher education, instructors should also try to devise active learning interventions that can spur genuine interest in the subject and foster student motivation. Moreover, philosophical or psychological underpinnings of the effect of active learning interventions would be an interesting topic of interdisciplinary research.

Support for science educators

Instructor knowledge about metacognition and constructivism is a critical factor that links active learning interventions to improved academic achievement (5,8,40,85-86). Acknowledging the need for instructor training, science education communities have developed workshops for faculty and postdoctoral fellows (e.g., Summer Institutes on Scientific Teaching; http://www.summerinstitutes.org) (87) and active learning databases (Table 2). However, these efforts can still be increased. As mentioned above, detailed documentations and toolkits of the active learning interventions and centralized platforms for sharing active learning strategies and assessment tools will help instructors fully achieve the potential of active learning interventions.

Just as in every other field in today's world, the education community should be informed and trained in newly available technologies that can make learning more dynamic and personalized. For example, instead of using traditional clicker systems, educators can use web-based tools, such as Learning Catalytics (www.learningcatalytics.com), to increase accessibility and offer various types of questions. Educational games and lab simulations can also promote active learning and increase student learning (78,88).

With advances in both technology and educational research, it can be difficult for some faculty to stay abreast of the latest developments. Perhaps instructors should be encouraged to amass credits (via workshops and conferences) toward "Continuing Pedagogical Education" much as is the case for practicing physicians with Continuing Medical Education.

Active learning in the online learning era

The domain of active learning interventions is expanding to the online space. MOOCs, or massive open online courses, emerged as a force that some argued would revolutionize higher education. As the name indicates, MOOCs exclusively use the online platform to offer instructional materials. During their expansion, MOOCs innovated online pedagogy and triggered educational research in online learning (89-96). With an increasing number of courses incorporating online learning in the future, there should be a strong demand for active learning interventions that can be used in online courses.

SCIENTIFIC TEACHING THEMES

Active learning

Active learning has taken center stage in undergraduate education. Students are no longer considered passive vessels that are mechanically filled with knowledge, but instead are challenged to play an active and autonomous role in their learning process. The successful and effective use of several active learning interventions has laid the groundwork for a more detailed investigation as to how these active learning interventions work and how instructors can apply them even more effectively to improve student learning. The evidence supporting the benefits of active learning and the resources available online should encourage instructors to incorporate these activities into the classroom.

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Table 1. Active Learning - Examples of popular active learning interventions.

Active Learning Technique	Description	Use = IC: in class; A: Assignment; G: Groups; I: Individual	Easy to implement	Easy to grade	Interactive	Quick feedback to Instructor	Higher concept learning	Long prep time	Takes considerable time in lecture
Brainstorming	Compilation of ideas to a given question/topic	IC, A, G, I	x	x	x	x			
Case studies	Application of concepts to a real life scenario	IC, A, G, I	x		x	x	x	x	x
Classical clicker question	Multiple choice questions answered via a special hardware; answers can be summarized and shown as bar graphs	IC, G, I	x	x		x		x	
Concept mapping	Graphical connection and organization of parts of a given concept	IC, G, I	x	x		x		x	x
Debating	Discussion of opposing view points	IC, G			x	x	x		x
Group exams	Collaboration on a take home exam	A, G			x		x		
Group projects	Collaboration on a given (or chosen) project	A, G			x		x	x	
Inquiry-based labs	Learning of lab techniques by stating a hypothesis and collecting experimental evidence	IC, G			x		x	x	x
Jigsaw	Learning in groups which allows each student to master different concepts, followed by the formation of new groups in which each student then teaches her/his peers the concept he/she just mastered	IC, G	x	x	x	x		x	x
Making exam questions	Writing an exam question which is based on the adaptation of conceptual knowledge	A, I	x	x			x		
One minute paper	Short (1 minute) individual brainstorming to a given question	IC, I	x	x		x			
Peer-review of writing assignments	Giving feedback on peer's writing assignments	A, I					x		
Problem-based questions	Application of concepts to analyze and evaluate data, design experiments	IC, A, G, I	x	x			x	x	x
Statement correction	Correcting incorrect statements	IC, G, I	x	x		x		x	x
Strip sequence	Placing events in order	IC, G, I	x	x		x		x	x
Student-led discussion	Discussion of concepts (e.g. via literature reviews) lead by peers	IC, G		x	x	x	x		x
Think-pair-share	Answering a given question individually first before pairing up with a neighbor to discuss and finally share the answer with the group	IC, G	x	x	x	x			
Web-based response questions	Posing different question types via a web-based software; answers can be summarized and shown in different forms	IC, A, G, I	x	x		x		x	x

Table 2. Active Learning - Selected online resources for active learning interventions.

Resource	URL	Notes
ABLconnect at Harvard University	http://ablconnect.harvard.edu/	An online database of active learning strategies sorted by activity type, learning goals, timeline, etc.
Center for Teaching Excellence at Cornell University	http://www.cte.cornell.edu/	The "Resources" section contains useful teaching tips, assessment tools, and strategies for inclusive teaching.
The Center for the Integration of Research, Teaching, and Learning (CIRTL) Network	https://www.cirtl.net/p/resources	CIRTL archived posters, guidebooks, reports and articles regarding innovative teaching methods.
CourseSource	http://www.coursesource.org/	An online, open-access journal publishing innovative teaching practices exclusively in biology.
Eberly Center at Carnegie Mellon	https://www.cmu.edu/teaching/designteach/index.html	The "Design & Teach a Course" section provides detailed guidelines for instructors designing new courses.
iBiology	https://www.ibiology.org/scientific-teaching/active-learning.html	A series of videos addressing topics and challenges related to active learning.
The Science Education Resource Center at Carleton College	http://serc.carleton.edu/introgeo/gallerywalk/active.html	The website lists various active learning strategies with their purposes and usages.
Teaching Commons at Stanford University	https://teachingcommons.stanford.edu/	The "Resources" tab contains tips for how to teach effectively, lead a discussion, evaluate teaching, etc.
Vision and Change in Undergraduate Biology Education	http://visionandchange.org/	Vision and Change reports are archived.