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Commentary

Active learning-based STEM education for in-person and online learning

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The COVID-19 global pandemic has forced the higher education sector to transition to an uncharted remote-learning format. This offers an opportunity to adopt active learning, which increases students' performance compared to lectures, narrows achievement gaps for underrepresented students, and promotes equity and inclusivity, as the basis of STEM education.

The word "career" etymologically derives from the Latin *carrus*, which indicates a wheeled vehicle or a wagon. The coronavirus disease 2019 (COVID-19) pandemic has put the brakes on the careers of millions of people worldwide and disrupted undergraduate and graduate education. Many students and scientists may feel as if the wheels have well and truly come off their scientific careers. With social distancing practices imposed, the higher education sector has been forced to transition toward an uncharted fully remote-learning format.

In normal circumstances, the rollout of online university courses would require significant time and resources to develop IT systems, design content, and retrain faculty. Despite the pressing need for a "new norm," these resources are unlikely to be readily available to all the universities now urgently in need of them. As a consequence, there is a real threat to educational standards. Therefore, the current situation threatens not only to jeopardize students' learning, but also to exacerbate global educational inequalities. Yet, in a time of uncertainty, new opportunities arise.

The pandemic has threatened that stalwart of higher education: the traditional live lecture, often with hundreds of students congregated in a crowded room to passively witness an instructor hold forth on the stage. This lecture format has

persisted as the mainstay of undergraduate (college) and graduate education in science, technology, engineering, and mathematics (STEM). Naturally, there is much wringing of hands that the pandemic is compromising the education of a whole cohort of students by denying them the benefits of live in-person lectures. Yet, examining published randomized controlled studies, there seem to be no differences in students' learning outcomes with online lectures compared to the in-person format (Table 1). However, despite the lack of differences in objective outcomes, a disadvantage of online lectures is that students feel less engaged and connected with the teacher and their classmates. In one of the studies, 69% of students randomized to online lectures agreed with the statement: "I feel that being able to interact with the lecturer in person in a classroom setting is a better learning experience than the online format"—despite the online lecture students performing better than live lecture students on a subsequent exam on the course topic (Vaccani et al., 2016). This finding highlights the importance of interactivity for student satisfaction.

That the transformation of lectures to an online format appears to do no objective harm to students' learning will undoubtedly provide reassurance for educators in this time of crisis. But rather than replicate the educational modus operandi in

an online form, the current situation represents an ideal moment to transform educational delivery by making active learning the basis of STEM education, uprooting the traditional format of lecture-based teaching.

Active learning: Theoretical basis and advantages

The traditional "passive" approach to STEM higher education is embodied in the lecture format, with students listening to experts who impart their knowledge (Figure 1A). In contrast, active learning involves students "doing things and thinking about the things they are doing" (Bonwell and Eison, 1991). In our careers as scientists, there are certain tasks we routinely do, regardless of our specific areas of expertise; for example, condensing analyses in a series of slides, writing an abstract, submitting a travel grant, or reviewing a manuscript. These tasks occupy a large proportion of our work, but explicit training in these activities is rarely offered at universities (Sandrone and Schneider, 2020). These are examples of active learning tasks. Within an active learning session, guided by an expert facilitator, students learn by, for example, "creating" or "applying" something relevant to the aims of the teaching session. Action words like these describe the "cognitive processes" by which students, individually or in groups, engage

Table 1. Randomized controlled studies comparing live lectures (LL) and online lectures (OL)

Study	Vaccani et al., 2016	Brockfeld et al., 2018	Chirikov et al., 2020	Musunuru et al., 2021
Subject	otolaryngology	medical knowledge	engineering	biochemistry
Location	University of Ottawa, Canada	University of Göttingen, Germany	three universities in Russia	Harvard College, USA
Participants	third-year medical students	medical students	second-year undergraduates	second/third/fourth-year undergraduates
Number of participants	148 (73 LL, 75 OL)	205 (4 groups)	201 (101 LL, 100 OL)	125 (groups of 61 and 64)
Intervention	three lectures in 1 week	crossover design: 41-day course, 4 h of lecture daily	weekly lectures for full semester	crossover design: weekly LL for 1 half-semester, weekly OL for other half-semester
Additional elements	none	none	weekly discussion groups	weekly small-group sessions
Learning assessments and outcomes	written exam 10–40 days later: LL = 19.3/27, OL = 19.5/27, $p = 0.69$; clinical exam up to 1 year later, LL = 12.5/19, OL = 14.1/19, $p = 0.008$	standardized exam after end of course: LL = 78.3%, OL = 78.6% (no p value provided)	covariate-adjusted final exam score, LL = 53.1%, OL = 52.3%, $p = 0.77$; covariate-adjusted average assessment score, LL = 74.4%, OL = 75.2%, $p = 0.80$	first half-semester: exam, LL = 43.1/50, OL = 43.2/50, $p = 0.70$; normalized learning gain[a], LL = 0.32 (max gain = 1), OL = 0.35, $p = 0.98$; second half-semester: exam, LL = 45.1/50, OL = 45.0/50, $p = 0.70$; normalized learning gain[a], LL = 0.35, OL = 0.29, $p = 0.54$
Selected survey information	in LL group: 43% agreed or strongly agreed OL was a better learning tool for them than LL, 28% felt neutral; in OL group: 55% agreed or strongly agreed OL was a better learning tool for them than LL, 33% felt neutral; 35% agreed or strongly agreed that they preferred to have most lectures in OL format, 20% felt neutral; 69% felt that being able to interact with the lecturer in person in a classroom setting was a better learning experience than OL format, 11% felt neutral	48% preferred LL, 27% preferred OL, 25% were neutral	covariate-adjusted student satisfaction: LL = 63.0%, OL = 60.5%, $p = 0.36$	40% preferred LL, 60% preferred OL; 23% felt LL better for learning, 54% felt OL better for learning, 23% felt both equally effective; activities during lectures: checked email, LL = 2.86 (1 = never, 5 = always), OL = 2.23, $p < 0.001$; chatted online or texted, LL = 2.37, OL = 2.26, $p = 0.58$; surfed the Web, LL = 2.24, OL = 2.07, $p = 0.21$; talked with others, LL = 2.03, OL = 1.47, $p < 0.001$; worked on other assignments, LL = 1.60, LL = 1.28, $p = 0.003$

[a]Each assessment of learning gain directly compared the scores of a pre-test and a post-test administered immediately before and after the intervention period.

Due to space constraints, we were able to include only a limited number of studies in this table.

with knowledge. The full terminology of active learning is described in the revised Bloom's taxonomy, one of the pillars of this learner-centered approach (Anderson et al., 2001).

From an andragogical viewpoint, active learning is an old acquaintance, not a new player: a corpus of a hundred active learning tasks has been available since the 1990s (Bonwell and Eison, 1991; Silberman, 1996). But it is only in the last decade that an evidence base for the role of active learning in STEM education has emerged. In this time, active learning has demonstrated several advantages over traditional educational formats for both in-person and online environments. It has shown superior benefits across educational levels in STEM subjects, increasing students' performance compared to lectures across disciplines, as demonstrated by a meta-analysis of 225 studies comparing active learning with traditional lectures (Freeman et al., 2014). Such active-learning-related performance increases ("learning gain") were recorded across all course types, course levels, and class sizes, although active learning proved to be especially beneficial in small classes (Freeman et al., 2014). Active learning reduces disparities and narrows achievement gaps for underrepresented students in these subjects and can promote equity and inclusivity in higher education (Theobald et al., 2020). More specifically, active learning reduced achievement gaps in exam scores and passing rates by a magnitude of 33%; while offering benefits to all students, it has a "disproportionately beneficial impact" for individuals from low-income backgrounds and students from underrepresented minorities (Theobald et al., 2020).

For in-person activities, there is no need to redesign the classroom architecture or add expensive technological devices to successfully implement active learning. In fact, no significant differences in grades have been found for the
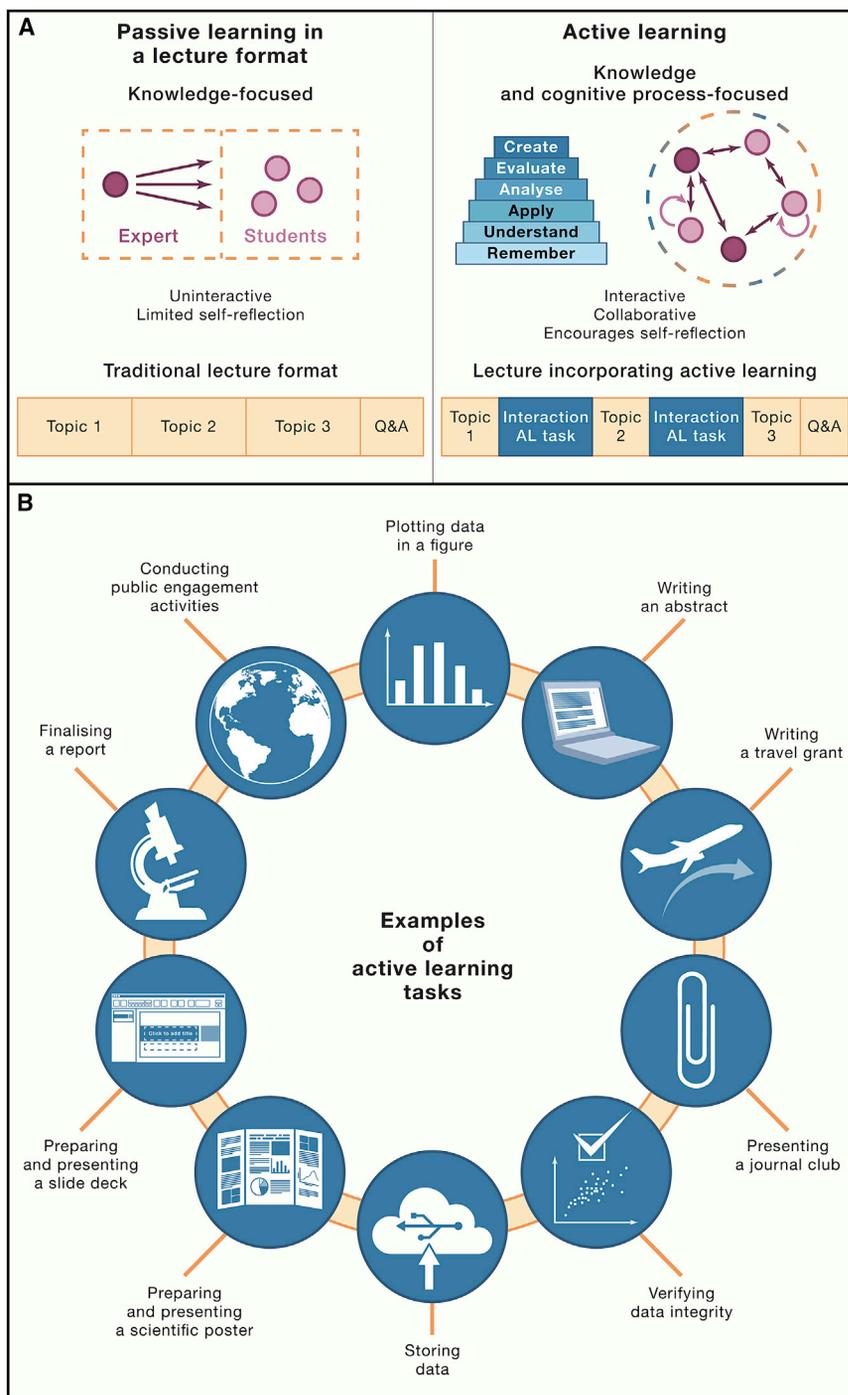
Figure 1. Transforming learning and educational interactions

(A) Passive learning in a traditional lecture format is characterized by a knowledge-focused model that allows limited interaction or student self-reflection. Instead, active learning within a community of practice, by focusing on both knowledge and the cognitive processes involved in working with that knowledge, fosters an interactive and collaborative learning experience. The pyramid is a graphical representation of Bloom's taxonomy.

(B) A range of active learning tasks that can be implemented in the curriculum, as individual or group tasks.

same course taught in a high-technology-based active learning classroom environment (where computers have been integrated at students' workstations) versus a low-technology-based one (the traditional model of desks and chairs, but with the instructor employing active learning methods) (Nicol et al., 2018). Even students' learning gain does not differ between high- and low-tech active learning environments (Soneral and Wyse, 2017).

As we have seen for lectures, the evidence suggests that active learning can also be successfully deployed in an online setting, as discussed in the following paragraphs. Even within an online environment, active learning engages students and maximizes their learning (Khan et al., 2017). The basic technology required for the successful delivery of active learning online is that participants have access to a device with an internet connection supporting two-way video calling.

In addition to learning gain, active learning improves learning outcomes by fostering community. In 1991, the anthropologist Jean Lave and the educationalist Etienne Wenger theorized the concept of "community of practice," where members learn from each other and develop on a personal and professional level by sharing common experiences, practices, and knowledge, a concept that was further explored in subsequent works (Wenger, 1998). Via both in-person and online settings, active learning can promote core community of practice characteristics, such as "becoming" and "belonging" (Wenger, 1998). These characteristics must be fostered during the pandemic to improve students' learning experience. All these concepts, along with the notion of students' engagement, are increasingly used in measures of student retention and in attempts to quantify the quality of teaching across universities. These are likely to serve as criteria to direct university funding and play a role in guiding students' university selection choices. Given the growing importance of such metrics and considering how active learning can favor these aspects, in the midst of uncertainty, the major adoption of active learning might prove to be a

competitive advantage for educational institutions for years to come.

However, the feelings of students toward learning within an active learning environment are often different from their feelings about the passive learning to which they are accustomed. While still positive, students' feeling of learning within an active learning format was lower compared to those who learned in a more traditional, passive environment (Deslauriers et al., 2019). Consequently, while students demonstrably learn more within an active learning setting, they may paradoxically feel like they learn less (Deslauriers et al., 2019). This misconception is often due to students' inexperience with the new active learning format and the increased cognitive challenges they experience within this cognitively demanding environment, especially at the beginning of its implementation, as opposed to the perceived "cognitive fluency" of the traditional lecture format (Deslauriers et al., 2019). Therefore, to counteract this, it is crucial to set students' expectations, explain the relevance of the active learning approach, and contextualize the activities within a broader career-related perspective, tapping into the students' motivation and engagement. As the course progresses, reminding students of the benefits of active learning might also be helpful.

Integrating versus replacing

The adoption of active learning does not necessarily mean the abandonment of the traditional lecture format. Instead, active learning encompasses a suite of approaches that can form part of an educational mix, providing flexibility in teaching delivery. There is certainly no one-size-fits-all solution. We provide examples of how active learning approaches can be incorporated into STEM education.

Instead of replacing the traditional lecture format, elements of active learning can be incorporated within lectures. To maximize the effectiveness of this approach, it is necessary to rethink the design of lectures. There are many options here, but a basic strategy is to divide a lecture into small units, each delivered didactically, and active learning tasks are included at the boundaries of these units

(Figure 1A, right). A rich palette of active learning tasks can be easily incorporated across the restructured lecture. As a bare minimum, repeated periods of audience interaction should be encouraged, such that students can check their understanding over time. This is simple in person and can be implemented easily over voice or video communication. The online environment has also opened up many more diverse opportunities for audience participation of this kind. Software like Mentimeter captures live questions or polling, whereas Panopto allows the insertion of questions into video recordings at specific points so that students can ensure they are comfortable with the material before moving forward. Other options include, either in person or online, quizzes, other polling systems, Q&A sessions, live problem solving with real data, and debates (Bonwell and Eison, 1991).

In-person or online synchronous formats allow these kinds of interactions, but it may not be possible to deliver lectures synchronously. Asynchronous viewing denies instructors the possibility of adjusting their teaching on the fly based on their live impressions of the audience's understanding. But there are advantages of asynchronous delivery. By providing students with online recordings of lectures, those periods of synchronous classroom time, be it online or in person, can be fully devoted to active learning tasks.

A range of active learning tasks is possible in both online and in-person settings. Active learning tasks can revolve around case studies, such as students applying the concepts they have learned to novel scenarios or think-pair-share questions (i.e., posing a question for students, allowing them to come up with answers, having them discuss their answers with peers, then discussing with the group at large). Additionally, web-based response questions can be designed for students to wrestle with critical scientific concepts: these can be individually answered via mobile phones or laptops and then discussed by the class at large. In addition to these, in Figure 1B, we offer examples of active learning tasks that can be deployed either online or in person, individually or in groups, providing flexibility for instructors who need to switch formats or are teaching

classes where some students are in the classroom and some are remote. Additionally, *CourseSource*, an open access online journal, provides instructors with materials to incorporate active learning exercises in a wide variety of biological disciplines.

Laboratory exercises provide a powerful form of in-person active learning. Yet they can still be delivered within an online environment, with potential to enhance students' learning experience. Experimental techniques can be demonstrated to students via videos made by the instructors or by using online journals with video demonstrations. These can be paired with short questions that assess students' understanding of the rationale for major steps in the protocol. There are online platforms, such as LabXchange, where students can perform virtual simulations and even troubleshoot experimental designs to gain practice with fundamental molecular techniques. Primary data can then be shared as if the students collected them by themselves. Students can analyze the data and draw meaningful conclusions. While, ideally, they would be gathering data themselves at the bench, the central component of laboratory sessions on data analysis, presentation of results, and drawing of conclusions is preserved— even if access to the laboratory is prevented. Using these skills to address novel scientific questions is key to developing students' critical thinking and problem-solving acumen.

Case study

Two of us (W.J.A. and K.M.) carried out a randomized controlled study with a cross-over design in an introductory college-level biochemistry course, randomizing students to either live lectures or prerecorded asynchronous online lectures covering identical content (Musunuru et al., 2021). Consistent with previously published works, no differences were observed in terms of achieved learning outcomes during the semester. Still, students reported a higher engagement level during online lectures than live lectures, and the majority (60%) preferred online lectures to live lectures (Table 1).

In addition, outside of the experimental intervention, all students attended weekly small-group sessions in an active-learning format led by one of the instructors. Each session was organized

around a patient case intended to illuminate key biochemistry concepts (one example is available at https://bit.ly/Fragile-X-protein-structure-case). Students were split into small groups and discussed the data provided as teams; they also debated the answers to open-ended questions intended to replicate the scientific investigative process, thus engaging in the higher levels of Bloom's taxonomy (Figure 1A). The instructor circulated through the room to serve as a sounding board and provided guidance to teams while gauging the level of understanding on the students' side.

In light of the positive feedback received from the students, the same active-learning, small-group, case-based format has since been applied to other courses, covering diverse topics such as human genetics and CRISPR genome editing (examples available at https://bit.ly/CRISPR-genome-editing-case, https://bit.ly/genetic-testing-case, and https://bit.ly/GWAS-cholesterol-gene-case). Even though all the sessions were conducted in person, the materials have been provided in a cost-free online format (Google Forms), suitable for laptops, tablets, and smartphones, to promote ease of accessibility.

This package of educational activities was transitioned to a fully online delivery format during the second wave of the COVID-19 pandemic in fall 2020. Prerecorded asynchronous lectures were made available, and the small-group sessions were conducted via an online platform (Zoom) with breakout rooms. Within the virtual breakout rooms, students could work together on the same cases, with the instructor circulating through the rooms, as in the physical classroom. With the course activities working equally well in-person and virtually—with minimal effort needed to pivot between the two formats—we see the use of asynchronous lectures paired with online case-based exercises as a model for instructors to emulate, both while the current pandemic is ongoing and afterward.

Post-pandemic STEM education: Revert or reboot?

When the pandemic has resolved, should we all reflexively move back to traditional, largely passive live lectures, or should we view our current circumstances as a golden opportunity to reboot STEM education? In our opinion, reverting to the pre-pandemic status quo would be a disservice to students and educators alike. The advantages of active learning should not be ignored. Compared to the traditional lecture format, an active-learning-powered STEM education offers opportunities to train in an interactive, practical way, concerned with the higher-order cognitive abilities demanded by a subject rather than simply knowledge.

Active learning tasks can be applied to any discipline and tailored to different levels of study. Educators looking to reboot their methods can embrace this flexibility by choosing which domain-specific knowledge to focus on and which cognitive processes to target. Educational delivery established in online formats will be more resilient to disruption from a new wave of the coronavirus or new pandemic. And in the midst of a crisis, by adopting active learning, we can improve not only current standards of educational delivery, but also transform educational practice for the long term.

There is a universe to be explored beyond the bricks and mortar of our universities. Even at a distance, we can train the next generations of scientists while offering an authentic, real-life, and, hopefully, inspiring learning journey. In the words of Antoine de Saint-Exupéry, aviator and author of *The Little Prince*: "If you want to build a ship, don't drum up people together to collect wood and don't assign them tasks and work, but rather teach them to long for the endless immensity of the sea." We can use several metaphors to depict our students' and our own careers, from a wheeled vehicle to a ship, or the aircraft piloted by the Little Prince. Whatever the vehicle, it is time to turn on the engine.

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