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On the path of scientific teaching.

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Abstract :
The treatment of pedagogy as a scientific subject, a process known as **scientific teaching**[1], has been ongoing for over a decade now[2 3 4], particularly in higher education STEM fields. The Howard Hughes Medical Institute (HHMI) has been at the forefront of this effort[5 6], investing over $100 million in a wide variety of educational initiatives[7] targeted across a diverse array of students, primarily at the university level[8 9]. Although the range of progress has been substantial[10 11], much work remains to be done. This review, though not exhaustive, will attempt to summarize some of the important advancements made thus far while also offering commentary on current and future challenges.
Keywords : Scientific teaching, active learning, education research, learning gains, assessment tools, authentic research experiences

The Road Traveled.

The fact that lectures are not a particularly useful medium for learning[12 13 14 15] is often credited to the work of Donald Bligh in the 1980s[16]. As can be imagined, this discovery was greeted with varying degrees of skepticism[17] since lectures were (and, in most countries, remain) the near universal medium for classroom learning[18 19]. Since the 1990s, a wide range of international research has confirmed lectures are indeed a poor medium for the long-term retention of information[20 21 22 23 24 25]. Perhaps even more important is the fact lectures are an ineffective way for students to acquire new skills[26 27 28], a pedagogical result of particular importance for STEM and other applied fields, where lab and process skills[29 30 31 32] (skills required to perform a physical or intellectual procedure) are often more important than content knowledge (facts, concepts, vocabulary, etc.). Add to this the fact content knowledge is now exceedingly easy to access across the internet[33 34 35 36] and one can come to appreciate how modern education (of STEM fields, in particular) has quietly undergone a shift in emphasis away from content acquisition towards more skill development[37 38].

The year 2004 is often regarded as the seminal moment for scientific teaching, the year in which Jo Handelsman and colleagues published their *Science* paper[1] outlining the need for a more rigorous approach to pedagogy, one steeped in the empirical verification of the effectiveness of both teaching technique and curricula. This moment coincided with the involvement of HHMI and the US National Academies of Sciences in supporting the expansion of scientific teaching[39]. Functionally, scientific teaching is the process of performing experiments on pedagogy to determine its effectiveness in improving learning gains[3 10]. These gains may involve improvements in knowledge retention[2 5 10 20], skill competence[8 26 27], or even attitudes towards a topic[11]. Over the last decade, a large volume of these experiments have been performed on virtually all aspects of teaching and learning: discovery-based inquiry[40 41], group discussion formats[42 43 44 45 46 47], the use of technology in learning[48 49 50], techniques for reading primary literature[51 52], and even the development of more diverse class access[53]. These efforts have begun to demonstrate large-scale improvements in both learning gains and student outcome across large tracts of STEM education, as best exemplified in the recent work by Freeman and colleagues[10].

Of the many content knowledge delivery formats tested over the years, one has emerged as a clear winner for STEM fields. This format is called **active learning**[54 55], often incorrectly referred to simplistically as "reversed design" or "flipping the classroom"[56 57 58 59]. Both of these latter concepts refer, in fact, to a single *component* of the overall active learning approach. Active learning at its core is a reorientation of in-class activities to facilitate and enhance student interaction so more class time is spent with students giving and receiving feedback from both instructors and student peers[60 61 62]. This enhanced interaction is often achieved by implementing controlled problem-solving activities. As has been demonstrated by a variety of international research, this reorientation results in substantial learning gains compared to lectures[1 10 11] as well as improvements in student grades[14 20 24 26 40 42 63], retention[64 65 66], and interest[67 68]. It is, in fact, very normal for every student to stay awake throughout the entirety of a properly built active learning class, something that can not be said for the average lecture.

In addition to improvements in the format of content delivery, another important advancement has been the development of a wide range of standardized **assessment tools** for quantifying various class elements[69 70 71]. Tools have been developed to quantify everything from knowledge retention[72 73 74 75] and skill competence[76 77 78 79 80 81 82] to student attitudes[83 84 85] and group-work dynamics[86 87 88 89]. In fact, the explosion of variety and specificity of empirically tested and verified education assessment tools has thus far been one of the greatest achievements of the scientific teaching movement, offering an ever widening range of instruments for use[90 91 92].

For STEM fields, undergraduate classes are traditionally separated into two formats: lectures and lab. From a scientific teaching perspective, these two are often reclassified as “content classes” and “skill classes”, based on the intended learning goals. Although the format of active learning is fairly well established now for achieving most content-based learning goals[93], its efficacy for skill learning is still actively being developed[94 95 96]. The main reason for this is the greater complexity and variety of skills in various academic settings and topic areas. The skill of learning how to design good experiments is, for example, decidedly different from solving a Mendelian genetics problem on paper. Although we often refer to skills such as "data analysis", "experimental design", or the ability to perform a PCR (polymerase chain reaction) as if they are single, isolated units, the truth is they are often quite complex, involving numerous steps and multiple possible variations based on available information or equipment. This makes skill learning a lot different from content learning, both in its delivery and assessment.

In recognition of this difference, a number of universities, most notably Stanford[97], have begun developing new education platforms for teaching lab skills. One of the more successful has been the development of **authentic research experiences** (AREs)[91 92 93 98], lab courses structured around authentic research in which students are given the opportunity to perform real research. This is in stark contrast to the typical cookbook lab course[91] in which a student is often simply asked to follow established procedures in yielding a known result. The added authenticity of AREs serves two purposes: 1) stimulate student interest and engagement while 2) giving students the opportunity to practice the common skills involved in authentic research, skills such as experimental design and troubleshooting. To emphasize these latter science process skills, students are often given the chance to design their own experiments and devise their own hypotheses, allowing a fuller and deeper scientific experience.

Another important advantage of AREs comes from the ability to directly train students in specific project areas that might already be in demand by faculty looking for students to join their research group. At Fudan University, we have recently begun operating a large-scale summer ARE program called BIOS, a program containing six topic tracks: cell biology, biochemistry, plant biology, fish genetics, mouse genetics, and fly genetics[99]. The experiments performed and learned in each track are created from existing authentic research projects in various labs and participating students are trained in two areas of their choice, learning a wide range of skills so they acquire full competence upon exit, putting them in a qualified position to join the parent labs of their selected tracks. In this fashion, ARE programs can be coordinated with real research groups to be used as organized conduits to prepare students for entry.

Under Our Feet.

There is still much work to be done in fully developing the scope and potential of scientific teaching. The first and most important is increasing the awareness that lectures are not an effective mode of instruction, to be used sparingly or replaced with alternative forms of pedagogy such as active learning[6]. Despite the large amounts of money spent by HHMI and direct advocating by the US National Academies of Science, scientific teaching has, overall, proved to be a hard sell, even in STEM fields[8]. Faculty, the vast majority of whom have relied heavily on lectures their entire academic careers[13], have largely been reluctant to change their teaching practices. Younger faculty, postdoctoral associates, and graduate students have generally been observed to be more receptive,[100] but even these have required organized and concerted efforts to prepare. The simple truth is the vast majority of teachers (postsecondary and otherwise) are either unaware of scientific teaching and its associated principles or reluctant to adopt them[12].

For universities, this issue of awareness often goes hand in hand with the structure and design of faculty recruitment. In the vast majority of cases, hiring protocols place heavy emphasis on research, leaving teaching as a distant, secondary concern[101]. This is despite the fact the majority of faculty salaries are actually budgeted from income derived from student tuition. Promotion and compensation for faculty is similarly directed towards research, especially in STEM fields[102]. Since teaching in a scientific teaching or active learning style also requires significantly more preparation than a lecture[103], the lack of incentive has also been repeatedly identified as a serious deterrent in enacting reforms. To this end, HHMI began sponsoring the "Summer Institutes on Undergraduate Education"[104], a regional series of conferences designed to educate faculty on the advantages and process involved in properly implementing scientific teaching and active learning systems.

Another important deterrent in enacting wider education reform has been the graduate student and postdoctoral training process itself[105 106]. In the sciences, virtually all training is focused directly on research and the ultimate creation of SCI publications. Although the typical science PhD program does require candidates to undergo two or more semesters of teaching[107], most schools have no organized curriculum for training students in scientific teaching or active learning. This lack, has, over the years, resulted in a global faculty population poorly versed in the mechanics of effective pedagogy despite recent advancements.

This result is even more pronounced outside of the United States. Although a large number of top universities in the US have recently begun actively pursuing scientific teaching by either hiring teaching professors to take over targeted areas of curriculum or establishing training programs for graduate students, postdoctoral associates, and/or faculty, other countries have largely been oblivious to this change. Since what I know of the European situation is largely anecdotal, I will restrict my commentary to the situation in Asia.

Despite the fact China, Japan, South Korea, Hong Kong, and Singapore are well known for prowess in the sciences, an awareness of scientific teaching and active learning has only just begun to appear. As far as I am aware, the programs I have developed at Fudan University in Shanghai and Dongseo University in South Korea are the only two properly-assessed scientific teaching systems in East Asia, systems that would meet basic quality standards promoted by HHMI and the US National Academies of Science. In Korea, I have conducted a number of surveys (yet unpublished) showing that some general awareness of the concepts of "reversed design" and "flipped classroom" have appeared among faculty in the last three years. Despite this awareness, every specific class design I have encountered has suffered from serious flaws, the most common being either the lack of proper assessment or an overall lack of understanding of how active learning mechanics work. In many cases, professors seemed to be under the misconception that flipping the class alone was a magic bullet that would solve education problems and automatically give learning gains.

In China, education reform in our hands has been stymied by the centralized codification of most class content into a lecture-based format, often with lists of topics that must be covered. A rigid administrative procedure accompanies this codification, making it challenging (but not impossible) to create alternative classes with different formats and content. Compared to Korea, awareness of active learning and scientific teaching is even less but since most universities in China have traditionally already enjoyed some separation of research and teaching faculty (particularly in STEM lab courses), I would say there is much more interest in China to learn new teaching systems. So far, the wider emphasis on education reform in China has been based on a big data approach, using student inventories of various sorts to correlate learning outcomes[108 109 110 111]. This is in contrast to the construction of concrete educational experiments driven by scientific teaching principles.

The Road Ahead.

In addition to fostering a deeper understanding and appreciation for active learning and scientific teaching, both domestically and abroad, three other important challenges lay on the road ahead. The first, as mentioned above, is the issue of graduate student and postdoctoral training. As individuals responsible for the future of our education system, it is critical these trainees are exposed to the principles and mechanics of active learning and scientific teaching as early as possible. Ideally, this exposure would be paralleled with an organized system of mentorship in which the trainees are allowed to apply and practice such systems in the classes they serve as teaching assistants. A number of institutions including Yale and the University of Chicago have created similar infrastructure but, thus far, participation has been voluntary, leaving much to be desired.

The second issue is incentivization. As mentioned above, converting skeptical faculty to alternative systems of pedagogy is challenging, especially when these faculty are predominantly hired for their research. As I have observed repeatedly during my time at Yale, the University of Minnesota, and in Asia, even faculty who recognize the advantages of active learning and scientific teaching are often reluctant to put in the additional work to convert their teaching into styles less oriented around lecture. For these faculty, monetary incentives are only occasionally motivating. Many institutions, such as University of Minnesota, have sidestepped this difficulty by creating a corps of professional teaching faculty responsible for lower-level core courses[112], relieving research faculty of the burden entirely. Although no one will argue with the effectiveness of this strategy, not every institution has the luxury to implement such an expansion. An alternative incentive for faculty is the prospect of manufacturing high-quality education publications. The problem with this goal is that it usually requires additional mentorship and experience, something most faculty do not have access to. At Fudan, one of the elements of the overall education reform program I have created includes this access, providing faculty with the support and tools to approach teaching as a research subject, one focused on the eventual publication of meaningful education data.

The final challenge, which I have made a point to embrace in recent years, is the transfer of active learning and scientific teaching systems to academic subjects outside the STEM fields. At Dongseo University, I currently run three pilot courses, one each in history, ESL (English as a Second Language), and science for non-majors, all built on active learning and scientific teaching designs. In each of these courses, we have observed substantial improvements in learning gains compared to lectures (not yet published), providing strong evidence that these systems are applicable across a wide range of academic subjects, albeit with some topic-specific behaviors we did not anticipate and are continuing to learn about. We expect the results from our work and that of others to soon permeate the educational literature, demonstrating the wide applicability of active learning and scientific teaching across disciplines.

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