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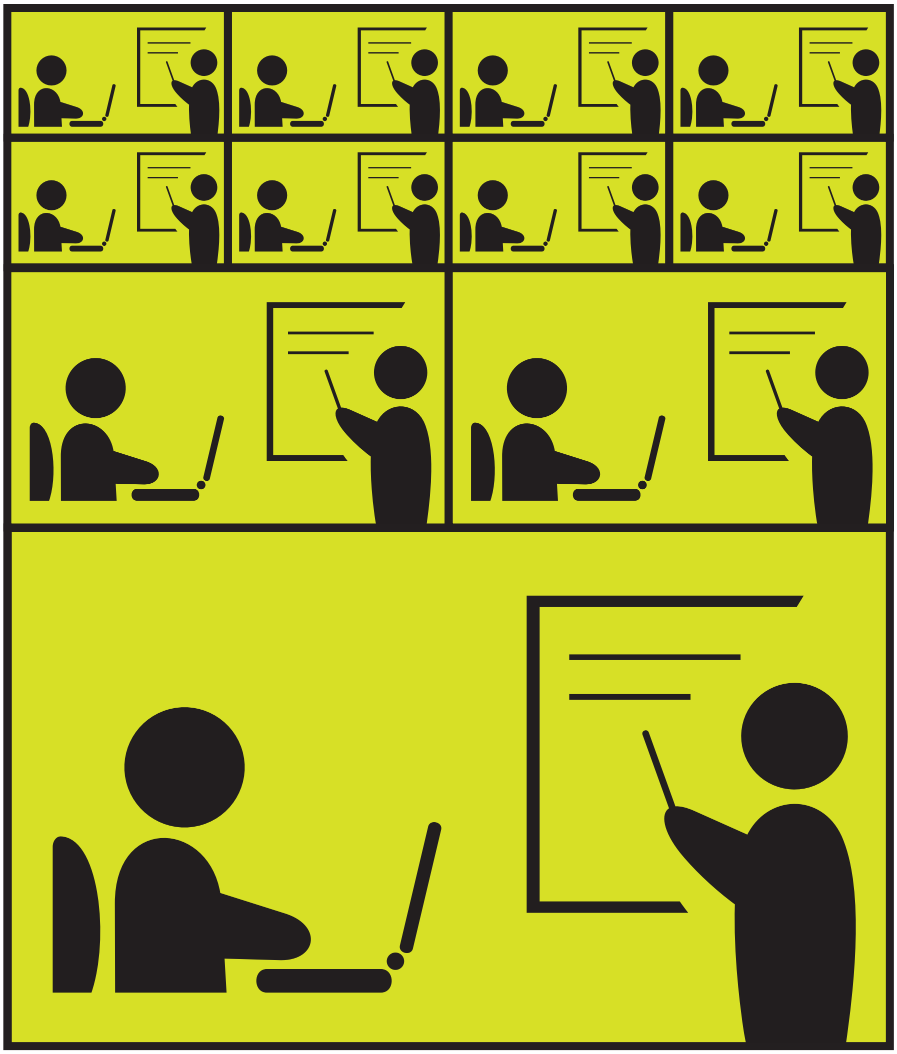
Viewpoint
Life After MOOCs

Online science education needs a new revolution.

THREE YEARS AGO, Moshe Vardi published an editorial in *Communications* expressing concerns about the pedagogical quality of massive open online courses (MOOCs) and including the sentiment, "If I had my wish, I would wave a wand and make MOOCs disappear."[9] His editorial was followed by studies highlighting various limitations of MOOCs (see Karsenti[5] for a review).

We share the concerns about the quality of early primitive MOOCs, which have been hyped by many as a cure-all for education. At the same time, we feel much of the criticism of MOOCs stems from the fact that truly disruptive scalable educational resources have not yet been developed. For this reason, if we had a wand, we would not wish away MOOCs but rather transform them into a more effective educational product called a massive adaptive interactive text (MAIT) that can compete with a professor in a classroom. We further argue that computer science is a discipline in which this transition is about to happen.



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When Will Massive Open Online Courses Disappear?

Was the printing press a worthwhile invention? This may seem like a silly question, but some of the backlash against early MOOCs reminds us of a criticism of the printing press made by the prominent 15th-century polymath Johannes Trithemius. Believing printed books were inferior to hand-copied manuscripts, Trithemius wrote, "The printed book is made of paper and, like paper, will quickly disappear."[8]

Anyone who has witnessed the beauty of a Renaissance illuminated manuscript can sympathize with Trithemius. Likewise, anyone who has attended a lecture delivered by a brilliant teacher in a small classroom can sympathize with Vardi. Yet in reality, contemporary higher education often falls short of this ideal.

The Case for Radical Change in Science Education

Large universities continue to pack hundreds of students into a single classroom, despite the fact this "hoarding" approach has little pedagogical value.[4] Hoarding is particularly objectionable in science, technology, engineering, and mathematics (STEM) courses, where learning a complex idea is comparable to navigating a labyrinth. In the large classroom, once a student takes a wrong turn, the student has limited opportunities to ask a question in order to facilitate understanding, resulting in a learning breakdown, or the inability to progress further without individualized guidance.

A recent revolution in online education has largely focused on making low-cost equivalents of hoarding classes. These MOOCs, which are largely video-based, have translated all of the pedagogical problems with hoarding into an even less personal forum online. In other words, MOOCs have thus far focused on being *massive*, when they should strive to feel *individual*. Rather than reproducing the impersonal experience of listening to a professor's lecture in a large auditorium, online education should move toward replicating the experience of receiving one-on-one tutoring in the professor's office—the most productive (yet expensive) form of education.[2]

Furthermore, the majority of energy a student invests in a STEM course is spent outside of the classroom, reading a textbook and completing assignments. But the traditional textbook suffers from the same flaw as a large class in failing to address *individual* learning breakdowns. And although some publishers have recently founded projects aimed at developing truly interactive learning resources, results have been slow in coming.

Since universities and academic publishers have failed to address these shortcomings, we are calling for a second revolution in online education. This revolution will focus on the creation of MAITs, a new generation of interactive learning experiences for STEM fields that can adapt to learners' individual needs and simulate the experience of one-on-one education.

Our call for revolution may seem like a lofty proposal, but we believe the time is ripe for a number of reasons. First, the rise of MOOCs has already established a competitive online marketplace, in which only the most developed courses in a given STEM discipline will have a chance of long-term success. Second, large

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investments are being made into sophisticated content platforms that can help improve upon the current video-based model. Third, a well-established research field is devoted to intelligent tutoring systems (ITSs), and next-generation electronic textbooks are already in development.[1,7]

Efforts in ITS research have attempted to address certain inherent limitations of the traditional classroom, such as: most instructors teach to only a certain percentile of the class; most students do not receive the immediate feedback necessary to prevent learning breakdowns; and most instructors lack information about the many different learning breakdowns experienced by individual students. Yet despite the promise of ITSs, as Mazoue[6] noticed, hardly any MOOCs have adopted ITSs. In light of the limited success of ITSs with the current generation of MOOCs, this Viewpoint defines a clear plan for how to make MOOCs truly disruptive by transforming them into MAITs.

What Is a MAIT?

A MAIT is defined by the following characteristics:

- Automated, individualized assessments;
- Interactivity;
- Adaptivity; and
- Modularity

Here, we illustrate these characteristics using our own experience in developing the *Bioinformatics* Specialization on Coursera, a series of six MOOCs followed by a Capstone Project[a] accompanied by a textbook.[3] In contrast to initial ITS developments, which have largely aimed at entry-level courses, *Bioinformatics* is a series of complex interdisciplinary courses aimed at upper-level undergraduate and graduate students that covers algorithms, biology, and programming.[b]

That we are MOOC developers may come as a surprise, since we have expressed doubts that MOOCs in their current form really represent a paradigm shift in STEM education. However, we see the creation of a MOOC as a natural first step toward producing a MAIT, and we are currently transitioning *Bioinformatics* toward a MAIT.

Automated, individualized assessments. When a student suffers a learning breakdown, that student needs immediate help in order to proceed. But traditional homework assignments are issued a week after the breakdown occurs. Teaching assistants (TAs) then must grade these assignments by hand, an undertaking that often proves repetitive. Furthermore, homework assignments are often unchanged year after year, and assignments at different universities have substantial overlap. Such a system makes no sense when grading in many STEM courses can be consolidated into a single automated system available at all universities.

In our call for automated assessments, we are not referring to primitive quizzes testing whether students are awake, but rather to robust assignments that require a sophisticated software system. Computer science is a unique discipline in that students' ability to program provides the opportunity to automatically check their knowledge through coding challenges. These coding challenges are far superior to traditional quizzes because, in order to implement a complex program, the student must possess a deep understanding of its underlying computational ideas.

Programming challenges already account for a significant fraction of assignments in many computer science courses such as introductory algorithms. However, thousands of computer science professors have implemented their own custom-made systems for grading student programs,

a See http://coursera.org/specialization/bioinformatics/34.

b https://www.youtube.com/playlist?list=PLQ-85lQlPqFM7jL47_tVFL61M4QM871Sv an incredible illustration of academic inefficiency. A MAIT therefore promises to build a common repository of programming challenges and a user-friendly environment for learners, thus allowing professors and TAs to focus on teaching.

For example, in addition to our MOOC, we contributed to the development of Rosalind,[c] a platform that automatically grades programming challenges in bioinformatics and allows a professor to form a customized Rosalind Classroom for managing assessments. In addition to Rosalind's 30,000 users, the Rosalind Classroom has been used over 100 times by professors wishing to incorporate its automated grading function into their offline courses. Grading half a million submissions to Rosalind has freed an army of TAs from the task of grading, thus saving time for interactions with students. Rosalind problems are individualized: the input parameters are randomly generated so no two students receive the same assignment.

Interactivity. A MAIT should incorporate elements of active learning. For example, *Bioinformatics* incorporates hundreds of "just in time" exercises and coding challenges that assess the student's progress at the exact moment this assessment is needed, facilitating the transition to the next topic. As such, *Bioinformatics* attempts to address learning breakdowns as soon as they occur.

A MAIT should also incorporate peer instruction, helping students interact with each other as well as with online TAs. If a learning breakdown persists after attempting an assessment, the student should be able to consult with peers who are having exactly the same breakdown. To achieve this goal, each paragraph of the interactive text powering *Bioinformatics* specialization is linked to a separate discussion forum.

Adaptivity. Most MOOCs incorporate elements of interactivity, but their educational materials are essentially static. In contrast, MAITs should be adaptive, an adjective that we apply in two distinct senses.

First, a MAIT should implement adaptive learning, meaning it can differentiate students' responses and guide them through the material on individual learning paths according to these responses. Achieving true adaptive learning is the most challenging aspect of creating a MAIT, since it requires far more work than creating a textbook or MOOC.

Second, in order to achieve adaptive learning, the MAIT itself must be adaptive, meaning that its authors must be willing to change its content perpetually. This property is missing in most existing MOOCs because revising a video lecture (even to change a single sentence) is costly.

To make a MAIT adaptive, its authors should initially generate a compendium of learning breakdowns. We recently generated a compendium for *Bioinformatics* based on the analysis of 8,500 discussion forum posts. This compendium is a pedagogical gold mine that has helped us continually revise our course and eliminate many learning breakdowns.

Creating a compendium of learning breakdowns has also been an eye-opening experience. We never could have imagined our students' ability to catch every tiny logic error, every minor detail we had attempted to hide. At the same time, our students encountered many unpredictable, superficially implausible learning breakdowns. Most breakdowns only affected a small percentage of students but were made apparent by the scale of the MOOC.

After generating a compendium of learning breakdowns, a MAIT's authors should be willing to write many special adaptive modules, each one presented only to students with a specific breakdown. Unfortunately, most current MOOCs are static, with limited changes introduced between consecutive offerings of the course. In our case, the creation of adaptive modules has nearly doubled the content needed for *Bioinformatics*. Assigning students to remedial modules should be done based on automated analysis of their responses, another important feature of a successful MAIT that will require future investment into data analysis.

Adaptive learning is a particularly attractive feature of MAITs in interdisciplinary fields.

Adaptive learning is a particularly attractive feature of MAITs in interdisciplinary fields. In these fields, students come from a variety of disciplines, and they often have gaps in their background and skills. In *Bioinformatics*, for example, biology, mathematics, and physics students typically lack knowledge of algorithms, whereas computer science students typically lack knowledge of statistics and biology. We have witnessed firsthand how automated assignments allow *Bioinformatics* students to succeed despite these gaps, but more work must be done to provide each student with an individual learning path through the course.

Modularity. Because the existence of a MAIT in a given field will likely flatten the textbook and MOOC markets in that field, some would rightly be concerned that a MAIT might lead to a rigid, standardized curriculum. To prevent this pitfall, MAITs should include an effort to modularize core content and provide resources for supplementing this content by additional crowdsourced learning modules.

An ancillary benefit of modularity is that a MAIT can serve as an educational hub for a community of educators. New professors teaching a subject for the first time can choose from an enormous menu of learning modules, while seasoned professors can contribute their own expertise to the growing project.

The Need for a High-Cost Development Team

Although professors creating new MOOCs often complain about the high cost of MOOC development, the cost of creating a MAIT will be much higher. We should cast aside the image of a professor on sabbatical writing a textbook or planning a new course from a

c See http://rosalind.info.

café in some exotic locale. Instead, the production of a MAIT requires an entire development team with a budget of $1 million or more.

Although this figure may seem preposterous, some educators, such as the developers of the Online Master of Science in Computer Science at Georgia Tech, have already invested comparable funds in developing their courses. MAITs should therefore be developed under the assumption that they have a sufficient budget in order to construct an educational product that can capture a large share of the MOOC market and truly disrupt both hoarding classes and traditional textbooks.

For example, *Bioinformatics* has already required over two years of development by a team consisting of professors, postdoctoral researchers, students, artists, and software engineers located in two countries and supported by three funding agencies and a private foundation. The total time investment made by this team was 50 times larger than the average of 100 hours required to develop a typical MOOC.[5] The majority of development focused on creating an interactive text to power the course; lecture videos—which are often cited as a major investment in MOOC development—accounted for only a fraction of our budget. Yet *Bioinformatics* will require substantial additional investment in order to become a MAIT.

The high cost of MAIT development immediately raises the question of whether it makes sense to develop a million-dollar MAIT for small online courses, for example, attracting "just" 10,000 serious learners per year. We note that because of the rising costs of textbooks, a MAIT attracting just 10,000 learners per year indicates a potential educational market of over $1 million per year. Furthermore, the high fixed cost of creating a MAIT is balanced by the negligible marginal cost of each additional learner. Finally, there are numerous opportunities to expand MAITs to developing countries, where the number of qualified professors is far smaller than the number of capable students.

The Future of MAITs

MAITs will eliminate the current model of hoarding classes practically overnight. Rather than attempting the futile task of creating a lecture that can be understood by hundreds of students from widely varying backgrounds, professors in hoarding classes will immediately see the inherent benefit in "flipping" these classes. In fact, some of our colleagues at leading universities have already used *Bioinformatics* to flip their classes. Rather than listening to lectures, students will complete assignments from the MAIT, which has already been fine-tuned to anticipate countless learning breakdowns. Energy the professor previously allocated to planning and delivering lectures can then be devoted to in-class discussions helping students understand complicated concepts, or even guided group projects that help them take the next steps.

In looking for ways to improve our teaching, we found ourselves not looking forward, but backward, at the pedagogical style of Socrates.

Yet although we believe MAITs will first disrupt hoarding classes, we see MAITs as a disruptive technology to all STEM courses, both online and offline. Even the most talented teachers of small, offline courses may use MAITs to flip their courses when they realize that MAITs free them to imagine new ways to inspire their students.

Indeed, using the resources of a MAIT in an offline course does not just facilitate a professor's transition toward a flipped classroom; it necessitates this transition. We observed this phenomenon in our own instruction of an offline course at the University of California, San Diego, which used the interactive text that powers *Bioinformatics*. Our flipped course blurred the boundary between instructor and TA and forced us to completely rethink these roles. When students arrived in class, they already understood the majority of relevant course material. We would then help them answer each other's questions about complicated concepts. We also divided students into small groups and guided them through additional challenge questions we had devised. As a result, class time was reinvested in direct interactions with students and group projects rather than preaching to them from a pulpit. It may sound like a strange way to run a course, but consider: Is this not the kind of educational experience students expect to receive when they enroll in a university?

We do not claim our flipped course has operated perfectly on its first attempts. However, its flaws have inspired us to become better educators in ways we never could have imagined. In looking for ways to improve our teaching, we found ourselves looking not forward, but backward, at the pedagogical style of Socrates. The irony has not been lost on us that our adoption of new technologies presented by online education forced our offline course to return to educational principles handed down from antiquity.

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