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ONLINE EDUCATION POLICY INITIATIVE

FINAL REPORT

Online Education: A Catalyst for Higher Education Reforms

APRIL 2016

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FOREWORD

We, Karen Willcox and Sanjay Sarma, are co-chairs of the Online Education Policy Initiative (OEPI). In April 2013, MIT President L. Rafael Reif launched the Institute-Wide Task Force on the Future of Education at MIT, charging groups of faculty, students and staff to explore potential future models of teaching and learning on campus and around the world, especially in light of recent advances in online education. We were privileged to co-chair that Task Force, together with MIT's Executive Vice President and Treasurer Israel Ruiz. The Task Force's final report, published in September 2014, can be found at future.mit.edu and represents 18 months of provocative and engaged conversation with the broader MIT community.

The Online Education Policy Initiative was undertaken as a follow-up to the MIT task force report, to consider the impacts of online education more broadly. The Carnegie Corporation provided generous support for the OEPI. We also appreciate support from the National Science Foundation for an accompanying workshop.[1] A number of faculty, staff, and researchers from MIT are members of the initiative, and our efforts are guided by a distinguished external advisory group. This, our final report, presents findings from discussions among the members of the initiative supported by advice from the advisory group. The report reflects comments and responses received on a preliminary draft from many sources, including education experts, government education officials, and representatives of university organizations.

We are both educators, and we are both passionate about teaching. In our careers we have individually benefited from inspiring teachers, and we are parents as well—and thus the beneficiaries of the dedication of our respective children's teachers. Yet the world is in transition in both the study and implementation of learning experiences, and this has resulted in questions such as, "Will online replace teachers?" We emphatically believe that the answer is "No." The role of teachers is essential and irreplaceable — rather, we believe that the value of in-person education can be *enhanced* by blending in online experiences." [2] The debate becomes particularly controversial in the context of the costs of education. Here too we believe that nuances are being missed and judgments are being rushed. What *is* urgently needed is a careful analysis of what we know about education and learning, and an analysis of the benefits of in-person and online models in different scenarios. This is the objective of the OEPI report.

In writing this report, it became clear to us that the question "Where does online education fit in higher education?" rapidly leads to existential questions about the what and why of higher education itself. The field is in such flux that a quick set of recommendations appeared neither appropriate nor convincing. Instead, we rapidly realized that a deeper dive was necessary into the many intertwined threads of research on learning, not just from traditional sources, but also from different perspectives. The report therefore "digresses" into deeper and broader examination of learning, and making recommendations about online learning in that context.

We feel it necessary to also delineate what this report is not. This report is neither a mandate nor a manifesto for the future of education. As a research university emphasizing science and engineering, MIT is not representative of all higher education. However, we do have significant experience in the development of online and blended education over the last two decades, both at MIT and at other universities. Drawing on this experience, the emphasis of this report is primarily on higher education, particularly in science, technology, engineering and mathematics (STEM) fields.

The Online Education Policy Initiative's discussions described in this report represent only the first step in a continuing dialogue. Our initiative set out with the goals of presenting a cohesive report on challenges and opportunities across the interacting subfields of education research, engaging in the public discourse surrounding the practice of online education, and influencing policy and policymakers to create a welcoming environment for educational innovation. We expect and welcome feedback on the ideas laid out in this report.

Finally, we are deeply grateful to the MIT participants in this activity and to the advisory group– they bring a rich range of experiences and perspectives to this activity, and have shaped the discussion presented here.

Karen Willcox
Professor of Aeronautics and Astronautics
Co-Chair of OEPI

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CHARGE OF THE OEPI

Given the accelerating changes in the landscape of higher education, and given the advances in learning science fields and in education technology over recent years, what are the implications of online education on higher education? What are education research, cognitive psychology, neuroscience and other fields telling us about how to improve education in both online and blended learning settings? How could these reforms be implemented? What are the policy implications for university presidents, for faculty, for policy makers, for funding agencies and for governments in the United States?

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We are grateful to William (Bill) Bonvillian for his invaluable contributions to this report.

EXECUTIVE SUMMARY

Historically, much of education research has focused on exploring the classroom as a context for learning, explaining the learning processes that occur in the classroom, and designing lessons that help students learn. The past decades have seen considerable research on the various social factors that affect learning; they have also seen increasing research into the effects of policy on educational attainment.

Often separately, advances in various fields of psychology, and now neuroscience, have allowed us to explain learning on several levels: an individual person, an individual brain, and increasingly an individual neuron. The research community is also exploring informal learning environments in much greater depth and has started to develop a variety of rigorous processes for learning design.

Despite this progress in a broad range of fields, conversations within the Online Education Policy Initiative have highlighted a need for further action in several important areas. Advances *within* the various fields of education are essential and should continue to be an important part of the agenda, but the transformative improvements necessary to meet the nation's pressing educational needs demand greater integration *across* fields.

It is imperative that this integration leverage the growing body of research that seeks to understand learning at the fundamental scientific level. Further, the field of education does not appear to have an integrated pipeline that promotes the transfer of concepts to reality. Online learning may be both an opportunity and a catalyst to achieve both these purposes.

Our findings target four areas: interdisciplinary collaboration, online educational technologies, the profession of the learning engineer, and institutional and organizational change. Focused attention in these areas could significantly advance our understanding of the opportunities and challenges in transforming education.

Recommendation 1: Increase Interdisciplinary Collaboration Across Fields of Research in Higher Education, Using an Integrated Research Agenda

First, we find that there is a pressing need in higher education for *deeper integration of research across the fields that impact learning*. In this report, we highlight a number of areas in which collaboration across fields has strengthened understanding of how learning works and helped improve design of effective learning experiences. These collaborations should be expanded and deepened for the future. In particular, there is a need and an opportunity to take advantage of the emerging convergence between what we term the outside-in approach (i.e., observing a system from the outside and making inferences about more detailed system functions) and the inside-out approach (i.e., starting with intrinsic explanations and building understanding outward) to learning research from across fields. Convergence of outside-in and inside-out research approaches has revolutionized fields such as biology and mechanics; we believe that education is on the brink of a similar revolution.

In recent years, the role of higher education in addressing broad socioeconomic challenges, such as income inequality and poverty, has frequently come to the forefront of public debate. Education is increasingly understood as a central enabler of societal advance. Development of a broad, integrated research agenda, we find, could help facilitate collaboration across research fields, focusing attention on how higher education might respond to specific societal challenges. In order to facilitate design of effective solutions, researchers from across the many fields related to education will need to work together—from the social scientists who study impact of education on social systems, to the researchers who explore pedagogical approaches and classroom structures, to the psychologists who study behavior and the neuroscientists who study learning processes in brains.

We find that these fields have been making important advances in recent years but have not been well integrated, so the opportunities for reforming the learning experience are not being fully realized. We recommend that government agencies (including NSF and the Department of Education), foundations, and institutions that support education research should encourage the development and execution of a coordinated research agenda. Many of these institutions have previously supported individual efforts to bridge the fields of educational scholarship, and they should continue to do so, but we are recommending an additional step. They should bring together leaders from multiple fields and advance-guard researchers at the boundaries of fields to agree upon problems and strategies for attacking them. A common research agenda that pulls in new findings from all fields of education and better integrates them could lead to powerful new insights. It would help build a community of versatile experts who can apply key findings to reform learning in online as well as classroom learning settings all across higher education.

Recommendation 2: Promote Online as an Important Facilitator in Higher Education

Second, we conclude that there are a number of significant and unique affordances provided by online education. These affordances allow for customization of learning, remote collaboration, just-in-time scenarios, continuous assessment and blended learning. They also importantly have the potential to support teachers, and to provide them with valuable insights into their students' learning.

We find digital technologies can play a significant role as an education enabler by providing a *dynamic digital scaffold*.

DIGITAL SCAFFOLDING

Online scaffolding enables "instrumented" learning. This helps make possible a number of promising additional learning approaches:

- Intersperse short videos with interpolated testing. This activates retrieval learning and mitigates mind-wandering. Most massive open online courses (MOOCs) already implement this strategy.
- Encourage recall of material learned a few days, weeks and even months ago. Spacing of practice is more conveniently implemented with online tools. Mix topics to encourage interleaving.
- Recall and highlight previously learned topics in the context of whole tasks. Steadily expand the scope of problems, enabling students to take on increasingly challenging tasks.
- Adapt to each learner's needs, revisiting topics where one struggles and adding materials or activities that address specific misconceptions another holds.

Additional digital scaffolding components which are effective in online and blended environments are discussed in the text. While online technologies are relatively young, we find they already show promise in providing learning support at a cognitive level.

We find that such scaffolding is already providing value in online learning. In particular, many online learning environments provide *spaced learning* to improve retention, which allows students and teachers to focus on applying that learning to challenging problems. Other online learning environments employ *game-based learning* which can contextualize abstract concepts, and provide data on student challenges back to the teacher.

We do not imply here that technology should or will replace teachers. In fact, we find that the evidence supports the intuitive sense that teachers are essential to learning in ways that a computer program can never be: by providing context and mentoring, and fostering reflection and discussion. We argue and recommend that new technologies should instead be used to support teachers and allow them to free up time from conveying content to focus on high-value in-person interactions with students. This approach aligns with the principles of *blended learning*, where technologies and teachers cooperate across online and in-person spaces. We find that blended learning can enhance learning, and requires reorganizing the learning experience to apply the different strengths of online and face-to-face learning.

Recommendation 3: Support the Expanding Profession of the "Learning Engineer"

Third, we recommend expanded use of *learning engineers* and greater support for this emerging profession. Improvements to the learning experience in higher education will not occur spontaneously. In our conception a "learning engineer" is a creative professional who helps build bridges between fields of education and develops additional infrastructure to help teachers teach and students learn. Learning engineers must integrate their knowledge of a discipline with broad understanding of advanced principles from across the fields of education. They must be familiar with state-of-the-art educational technologies, from commercial software to open-source tools, and skilled in the effective use of new online tools. Moreover they must be able to work with educators, both to create new learning experiences from scratch and to integrate new technologies and approaches into existing experiences, whether online or in-person or both.

We propose a new way to look at the design of learning experiences and their implementation which relies heavily on learning engineers to stimulate improvements at scale. This report explores a number of possible avenues for training and supporting the learning engineers needed to meet growing demand and to facilitate conversations across the fields of research in education. As they continuously work to translate the research literature into effective practice in local contexts, these learning engineers will by necessity integrate findings from different fields in their designs. We suggest that the development and deployment of a cadre of such learning engineers may be prerequisite to the wide introduction of the learning reforms suggested here.

Recommendation 4: Foster Institutional and Organizational Change in Higher Education to Implement These Reforms

Fourth, we discuss organizational approaches that have been applied to introduce transformation in other sectors and we discuss their potential applications in higher education. Reforms languish without an implementation model. In particular, we recommend the creation of ***thinking communities*** to continuously evaluate the kinds of education reforms proposed here, and the identification and development of ***change agents*** and ***role models*** in implementing these reforms. Here, we refer to change agents as groups of experts collaborating toward a common end, rather than just individual visionaries, and role models as successful groups and institutions that are willing to pilot new, thoughtfully designed approaches. But we must do so with the understanding that in legacy sectors like education change will not happen overnight.

We issue these four recommendations to stakeholders in higher education as a call to action.

Institutional leaders can foster change—embracing new learning processes online, in their classrooms, and elsewhere on campus or in their community; developing new organizational structures that serve a diverse population of students with a variety of professional educators including discipline-based education researchers and learning engineers as well as traditional faculty; recognizing, encouraging, and then rewarding interdisciplinary collaborations seeking to advance both the science and the practice of learning.

Legislators and government officials can show their support for educational innovation through strong budgets, novel program opportunities, and clear, forward-looking regulatory actions. They can help create a welcoming environment for interdisciplinary education research and for collaborative efforts to translate research into practice.

Legacy education companies can contribute experience in many areas, such as curricular design and delivery at scale and can accelerate the adoption of science-based learning practices.

Foundations and associations can convene, support, and disseminate, collectively representing networks of stakeholders with limited resources for direct participation.

Education researchers must come together and work together to make sure their scholarly gains are translated into real improvements for students, based on the best science and the most promising opportunities. Digital learning tools offer a dizzying array of opportunities for rapidly scaling best practices in many modes of higer education—residential and non-residential, purely online and blended. Researchers must guide the selection and development of these best practices if they are to help us bridge the gap between research and practice. They must move beyond their silos to work as a broad community, agree on terminology and ontology, map out overlaps and gaps, and recognize areas of discord. Then they can identify paths forward to a more equitable, more available, and more effective system of higher education drawing on best available tools and best available science.

1. THE COMPLEX SYSTEM KNOWN AS EDUCATION

Higher education is a complex multi-layered system. In formal education, the processes that occur in the classroom and informal study are central to learning, but important factors both larger and smaller in scale than the classroom affect outcomes. Science and engineering fields often attempt to model complex systems by delineating the factors that introduce variables into the system, and this is the approach we introduce here. Unless we have a general picture of the system, it is hard to consider the new variables that can induce change.

In the model shown in Figure 1, the learner and her immediate learning environment are embedded in an institution of higher education (e.g., a residential educational institution or an online course provider). This institution is itself surrounded by additional layers representing the influence of the local community, the nation, and the global context (including contributing factors such as prevailing ideologies, standards, funding, political climate, and more). Other layers around the learner represent factors whose impact may be more individual, including those associated with socio-economic status, health and nutrition, support systems, social milieu, and psychology. Many factors affect the learning process, and many fields of research contribute to our understanding of these factors and the process as a whole – Figure 1 depicts those fields that are discussed in this report. Within these fields, researchers apply a variety of perspectives at varying scales.

One example of the multi-scale nature of education research is in the study of the processes of learning. Many areas of psychology may have a bearing on the student's performance, including cognitive psychology, behavioral psychology, and non-

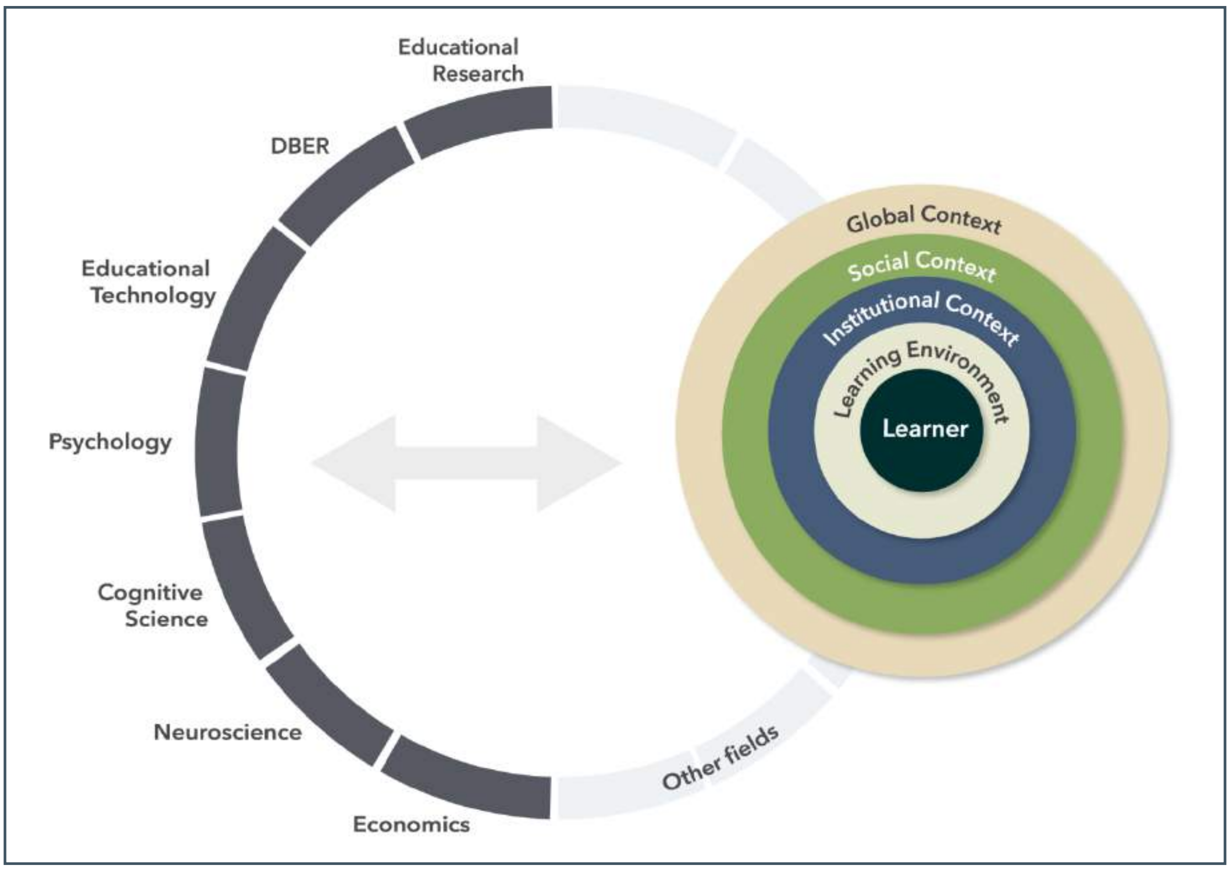

Figure 1: Many fields of research contribute to the study and advancement of the complex system of higher education

cognitive factors such as motivation. As indicated by the arrows in Figure 1, this influence is two-way; it is through the study of students that researchers in each of these fields of psychology advance their understanding of learning processes. One can delve a level lower, into how the human brain functions during the process of learning. Within the brain are components such as the hippocampus, which plays a vital role in memory formation, and the amygdala, which controls emotion and motivation. Each of these components is composed of different types of neurons, 100 billion of them in total, and the whole system operates on the basis of underlying mechanisms such as the electrochemistry and biochemistry.

Some domains of education research seek to understand the current state of learning and learning environments, and to discover and describe ways in which these environments affect the learning process. Others map the processes of learning at various levels, from the classroom to the individual to neurological functions that define learning, and study the impact of various external and internal factors on these processes. Still others measure the broad socioeconomic value of learning and seek to understand how best to make education accessible and useful to all. In addition, discipline-based education researchers seek to develop curriculum, scaffolding, and assessments that promote learning in specific areas of knowledge such as physics or biology.

Given the complexity of these many perspectives on education, it is no surprise that the field, especially higher education, draws continuous debate. The goals of educators and institutions vary, but share a common core: to enable students to grow as human beings, to master the topics they are learning, to enjoy and appreciate these topics, and to learn to apply them in life for enjoyment and for a livelihood. The many trade-offs include, among others, costs, efficacy, flexibility, transferability, and modularity. Recent public and policymaker concerns about growing costs of education and levels of student debt have put these trade-offs into stark contrast within a national conversation, and have resulted in a number of pointed questions: Is education worth the increasing costs?[3] Do the actual data on net tuition and debt per student support public and policymaker perception of a crisis in higher education? Are student-loan debt levels overly detrimental to college graduates' early career opportunities?[4] Does every student need a four-year degree?[5] Can diverse and disparate credit be reconstituted toward a new degree?[6] What is the role of certificates and badging?[7] Can education be unbundled entirely, or can it be reshaped into new packages designed to train specific skills?[8,9] Can time spent on coursework be replaced with competency testing of experience that results in the same learning?[10]

The rise of online education, particularly the recent growth of massive open online courses (MOOCs), has helped to bring attention to these important conversations but has also complicated the debate. While basic distance education goes back many decades, MOOCs bring new advances in scale and the degree of interactivity, sophistication, and personalization to distance learning, and a new opportunity for education at scale. The "massive" in the acronym "MOOC" is made possible by asynchronous video, by forums (which enable crowd-sourced student help), and by automatic assessments (which enable massive numbers of students to receive prompt formative and summative assessments). Furthermore, the "open" in the MOOC model aims to democratize education by making enrollment in the course free;[11] MOOC platforms such as edX and Coursera do, however, charge for certificates for these courses since more costly person-involved assessment is involved.

Some see online education, particularly MOOCs, as the solution to problems in education. There have been attempts to legislate transferability of online credit to state universities.[12] Others have viewed MOOCs as inimical to residential education, and as a cheap alternative to true learning.[13] Meanwhile, students have voted with their feet. Today, Coursera and edX together have over 15 million unique enrollees from nearly 200 countries. The growth of online education creates another dilemma: how do we enable students to construct meaning and make connections as learning becomes disaggregated?

Partly in response, in recent years we have seen increased introspection among universities on the value their residential experience brings, as well as examination of their business models and of issues such as pedagogy and learning strategies. Few can argue that this is an unwelcome outcome.

It was in this context that the President of MIT launched the Institute-Wide Task Force on the Future of Education at MIT in April 2013. The task force examined many of the questions listed above. Its final report, published in September 2014, can be found at future.mit.edu. The Online Education Policy Initiative was initiated as a follow-up to this report with the generous support of the Carnegie Corporation, as well as an important award for a related workshop project by NSF. The Initiative's charge was to examine the opportunities and the issues that online education raises in higher education in the U.S. This, our final report, presents findings from studies by the MIT members of the initiative, and is based on internal discussions and the advice from the distinguished external advisory group of the initiative.

Online education is an emerging part of the education system today, used in many different forms and implementations, and its success or failure will be determined by the broad trends and circumstances governing that system. In order to better understand the potential for effective development, we begin with a review of recent literature in the learning sciences looked at from different perspectives.

2. THE INTERACTING SUBFIELDS OF EDUCATION STUDIES

Historically, many fields of research develop "outside-in" (starting by observing a system from the outside) first and "inside-out" (starting with intrinsic phenomenological explanations and building understanding outwards) second. Consider zoology and botany. Both topics started as observational sciences, studying animals and plants. Key fields were morphology, anatomy and taxonomy, whether through the dissections of Vesalius or the classification system of Linnaeus. Gregor Mendel initiated the turn from the outside-in to the inside-out by identifying traits and heredity. The breakthroughs of the 20th century have given us an understanding of biochemistry, molecular biology, and DNA and gene expression, enabling a ground-up explanation of biological systems.

When outside-in study confirms inside-out models, unprecedented creativity is unleashed. Exciting areas such as genetic engineering and synthetic biology are a direct outcome of this convergence today. This pattern is evident in other disciplines as well; thermodynamics began with an outside-in approach, while statistical mechanics worked from the inside-out. The convergence of the two directions enabled a new mastery of everything from engines to nuclear power plants.

Consider one slice of the education landscape, shown in Figure 2. Education research has focused largely on interventions at the classroom scale and above for more than 100 years. Cognitive psychology, which focuses on the human mind as understood through observable behavior, has also been a rich field of research for over 100 years. As with many academic fields, cognitive psychology and education have evolved into mostly independent silos, often in different departments or different schools in the same university. Neuroscience, which is concerned with the nervous system, neurons, and the behavior of the brain explained inside-out, is often categorized as a branch of biology and has evolved in the last 100 years into yet another silo. Here we see just three of the many fields of study that can have a tremendous impact on education but are largely separated in study.

Education research has largely been outside-in in its experimental designs. Neuroscience provides an inside-out model for tackling many of the same issues from a different perspective. Cognitive science is an interdisciplinary field that emerged from a number of fields including artificial intelligence, linguistics, philosophy, cognitive psychology and neuroscience. Integration between the inside-out and outside-in models of research is a powerful combination, and could have a broad positive impact on the sophistication of these fields and perhaps on the learning sciences as a whole.

Figure 2: Outside-In and Inside-Out Views

We already are beginning to see advances in places where these walls are breaking down. While a complete understanding of the brain is decades in the future, significant advances are being made in fundamental understanding of its workings in areas such as memory formation, motivation, and mind-wandering. In the short term, it is possible to build a number of bridges through an expansion of basic research and collaboration between the fields of education research and cognitive science. A broader merger would involve all the other fields listed in Figure 1, and would grow dynamically as more connections and couplings emerge. Our internal and external conversations have highlighted the siloed nature of fields in the learning sciences as a key obstacle to advancement in a broader understanding of learning. Silos play into the further challenge of making practitioners aware of the research.

The preceding paragraphs describe one area in which we believe disciplinary boundaries between related fields can be bridged to substantial benefit. There have been many calls and attempts over the years to bring the varied fields in the learning sciences together. Examples, which will be explored in greater depth later in this report, include the work of the Institute for Research on Learning in Palo Alto, California, the Discipline-Based Education Research (DBER)[14] report commissioned by the National Academies, various academic programs integrating fields of learning science including master's degree programs in learning design, and the Simon Initiative at Carnegie Mellon University, among others.[15] In the next section we review advances in the various areas of research, identify synergies, and also explore the reasons behind their divergence.

Memory

Nobel Laureate Eric Kandel lays out his journey in the study of memory in the biographical book *In Search of Memory: The Emergence of a New Science of Mind*. Initially interested in studying the brain outside-in, Kandel switched to studying the mechanisms of memory in the California Sea Hare, *Aplysia californica*, at a very granular level, one neuron at a time. Over the course of his extraordinary career, he was able build an inside-out view of memory mechanisms. The book, which has chapter titles such as "Synapses Hold our Fondest Memories," uses fundamental principles to explain macroscopic topics such as mental illnesses, pharmacology, and psychoanalysis.

3. BACKGROUND: ADVANCES IN TOPICS RELATED TO EDUCATION

We first summarize below major developments from research in three large fields: education, cognitive science, and neuroscience. Significant advances have occurred recently in each of these fields, but they remain largely isolated from each other. Advances from individual fields should of course be better accounted for in designs for learning in classroom, blended or online settings. But education will benefit even more if these research communities integrate their efforts, potentially converging on parallel “outside-in” and “inside-out” patterns of progress that complement each other and accelerate change.

We then discuss efforts by STEM practitioners to improve teaching and learning in their disciplines, and perspectives from social science that underscore the importance of higher education. Developments in education technology are also reviewed, with opportunities noted for ways they can enhance learning. Progress on learning assessment using new “big data” approaches is noted, as are developments in other fields, such as work on rewards, motivation and classroom design. This broad survey of relevant developments in each of these areas sets the stage to make recommendations that would serve to bridge research areas and to integrate advances across fields.

Key Fronts in Education Research

It is impossible to adequately survey the entire rich field of education research in this relatively short report. We limit our attention to key topics relevant to higher education, focusing on pedagogies, practices, and principles that can guide the construction of online learning environments. These include pedagogies such as constructivism and situated cognition, practices such as flipping the classroom and integrating disciplines, and principles such as creating methods that work in practice and solutions that can be scaled. A brief overview of these topics is provided here.

There are several broad and influential directions of thinking in education. One of the most visible recently is active learning. The history of active learning can be traced to ***constructivism***, an approach first espoused by John Dewey as experiential learning, and formalized by seminal education researchers including Jean Piaget, Maria Montessori, and Lev Vygotsky. Discovery learning is a broad approach in which students use inquiry and discovery to construct knowledge.[16] In higher education, ***active learning*** is usually discussed in contrast to passive “chalk and talk” lectures.[17] While the idea of teaching laboratories, as a form of authentic experience supplementing lectures, goes back to Amos Eaton and his chemistry lab at Rensselaer in 1824,[18] modern approaches such as learning by inquiry and discovery-based learning are more integrated or replace the lecture entirely. Physics education researchers have led several waves of innovation in this area. Harvard’s Eric Mazur, for example, has championed a particular form of active instruction employing concept questions, clickers, and peer learning in the lecture hall.[19,20] Dickinson College’s Workshop Physics[21] pioneered the concept of the all-hands-on introductory physics course, which evolved through Rensselaer’s Studio Physics,[22] and North Carolina State’s SCALE-UP.[23]

At MIT, where W.B. Roger’s 1864 suggestion of a physical laboratory was implemented by Pickering five years later,[24] students now sit in small groups and learn introductory physics through mini-lectures, simulations, and desktop experiments in a specially designed Technology Enhanced Active Learning (TEAL) classroom. As described further beginning on page 11, curricula built around active learning and facilities supporting active instruction have become increasingly common in physics as well as other subject areas, especially in STEM fields.

Online learning environments are also increasingly being designed with active learning and interactive elements in mind. Proponents of online video content, such as Khan Academy founder Salman Khan, have pushed the idea of an active classroom further.[25] Khan, who coined the phrase ***flipped classroom***, imagines a learning structure where students watch video before coming to class and work on solving problems or engaging in discussions in the classroom. The ICAP framework provides a comprehensive approach to classifying different levels of active learning.[26]

A second offshoot of the constructivist philosophy is ***project-based learning***.[27] The connection between project-based learning and technology in STEM fields is long and storied. One of the first popular examples, The Adventures of Jasper Woodbury,[28] provided context for mathematical and scientific investigations via video disk. In mathematics, the work of Jim Kaput and colleagues on SimCalc[29] brought project-based explorations of mathematics concepts through calculators and personal computers. The nature of such projects in project-based learning has evolved over time, tracking the evolution of supporting technology. As technology has become more mobile, projects can now integrate hands-on and digital activities through hardware like sensors and probes, building on the uses, for example, of Microcomputer-Based Laboratories in physics[30] (see also page 11).

Seymour Papert defined ***constructionism*** as a refinement of constructivism with a focus on learning by making, and Papert's influence and ideals led to the development of a number of educational technologies including Logo,[31] Mitch Resnick's Scratch,[32] Lego Mindstorms,[33] Woodie Flowers's classroom robot design contests,[34] FIRST Robotics (co-founded by Flowers and Dean Kamen) and more. Many of these combine project-based learning with design and design thinking,[35] guided by the idea that projects give context and motivate learning more organically than the "sage on the stage." The availability of rapid prototyping technologies such as 3D printing and the Arduino microelectronics suite, and the growth of the "maker movement," have led to the creation of "maker spaces" in universities to help further the creative instincts of technical students.[36]

The Conceive–Design–Implement–Operate (CDIO) methodology, a programmatic approach to learning by doing which originated in MIT's Department of Aeronautics and Astronautics, has now been implemented in several universities around the world.[37,38]

Problem-based learning takes this approach a step further. By exposing students to imprecisely defined problems instead of artificial questions, problem-based learning ideally prepares them more effectively for the real world.[39] Project- and problem-based education also encourage students to participate in self-directed learning, peer learning and teamwork, and helps them hone their presentation skills. A problem-solving approach has also been shown to improve diversity—for example, a report from the American Association of University Women shows how Harvey Mudd College has used this approach to dramatically improve gender diversity in the study of computer science.[40] Finally, the integration of internships and work-study programs further blurs the boundary between college and the workplace.

A further extension of these trends has been referred to as ***student-centered education***. Key methods emphasized in student-centered programs are reflection, discussion (with peers and with experts), interdisciplinary thinking, self-paced learning and (in some formulations) mastery learning.[41] Bloom laid out the challenge in a seminal paper comparing conventional lectures, mastery learning, and tutoring: he showed that significant improvements in outcomes were possible, but asked whether this could be scaled.[42] The student-centered approach has been practiced at some colleges and universities for many years, most commonly in the humanities, arts, and social sciences; the traditional seminar format shares many features with the "flipped classroom." The Oxbridge tutor model, where students receive individualized mentoring in small groups, encourages peer learning and is partially self-paced. Student-centered programs at the secondary school level include Philips Exeter Academy's Harkness method, in which small groups of students "come to class prepared to share, discuss, and discover" around an oval "Harkness table."[43] Singapore University of Technology and Design (SUTD), a new university established in 2010 as a collaboration between Singapore and MIT, brings together many concepts of student-centered learning.[44] At SUTD, lectures are minimized; students learn in cohorts; and problem solving, collaboration, projects, and design are key activities.

To the surprise of some, peer learning, which has been mentioned as a feature of several of the above trends, is proving to be especially important in online courses. Online communication with peers has been shown to improve performance.[45] But face-to-face communities of learners participating in an online course have also emerged around the world, filling an apparent interpersonal vacuum with peer instruction and support. Online courses seem to allow students to adjust their peer exposure depending on personal taste,[46] and particular online platforms (with different built-in peer tools) may appeal to various students just as some residential students choose large universities and others prefer small colleges. Peer2Peer University (P2PU) is an innovative example of a learning environment in which the peer is the primary instructor.[47] There is also an emerging gradation among the diverse "peers" participating in MOOCs. More knowledgeable or experienced students are evolving into "community teaching assistants" who provide further social fabric and instruction.[48]

Studies of the efficacy of peer learning are examples of another significant body of research exploring ***social and contextual aspects of learning***. For example, there is early evidence that, although there may be cognitive benefits from online learning, the absence of social contact impacts motivation.[49] There is also evidence that in-person tutoring is effective,[50] and that watching peers tutor each other on video – an online practice that mirrors problem-solving sessions in residential education-- is more effective than watching a lecturer on video.[51] Finally, there is evidence that context of learning plays a major part in learning.[52]

The importance of context and application in learning is emphasized in the field of situated cognition, which is directionally aligned with learning by doing.[53] In many ways this is embedded in a founding principle of MIT: *mens et manus,* or mind and hand. Another example is the cooperative education model practiced at the University of Cincinnati, Northeastern University and Drexel.

Interdisciplinary education, which seeks to break down the silos of the traditional college,[54] is a prominent feature at several institutions, but its impact is not well studied. Singer has reviewed the available literature.[55,56] Concept maps enable students to map knowledge,[57] and are also a valuable tool for connecting across disciplines.[58] SUTD walks first-year students through world culture using a new international version of the "great books" course (an approach developed at the University of Chicago and Columbia in the years following the First World War and practiced to this day in its original form at St. John's College). Interdisciplinary design projects cut across the SUTD curriculum and research programs; there are no independent schools or departments. Every student takes seven courses in humanities, arts, and social sciences, and degrees are awarded in general engineering rather than specific disciplines.

The discussion thus far indicates a spectrum of educational techniques from the highly structured to the unstructured, with the recent trends toward unstructured approaches with an emphasis on inquiry, discovery, and active engagement. Both extremes, however, have drawn criticism. Highly structured courses, with tightly controlled learning objectives, are seen as providing accountability at the expense of integrated learning.[59] On the other hand, pure discovery learning has been criticized for not providing enough guidance to the novice,[60] and for leading to cognitive overload.[61] Efficient acquisition of expertise seems to require some structure, which can be provided through deliberate or guided practice.[62] Deslauriers et al. report benefit from using deliberate practice in a large physics class.[63] Several researchers have proposed formal techniques for introducing structure into student-centered learning, including ***fading scaffolds***,[64] ***task-centered instruction***,[65] and ***instructional design for complex learning***.[66] Important concepts emphasized by Van Merrienboer et al. are managing cognitive load through scaffolding; integration of knowledge, skills and attitudes across learning objectives; and instructional design that encourages transfer of learning to new problem domains.

Cognitive Science and Learning Research

The study of learning from the perspective of cognitive psychology has progressed greatly since the time of Ebbinghaus and his research on how memories form and persist.[67] A number of recent studies have implications for the design of online learning environments. Several specifically inform how we might best deliver online content. While philosophically, this contrasts starkly with the constructivist and student-centered approaches discussed above, we must consider ways in which these practices can effectively be integrated to promote learning for all.

We start with "mind wandering," an issue that has troubled educators for a long time. The mind wanders naturally, and the focus of the brain falters in time as "task-unrelated thoughts" gain hold.[68,69] This phenomenon has now received significant attention from cognitive psychologists[70] as well as from neuroscientists. Psychologists have shown that formative assessments interspersed with content delivery discourage mind wandering as well as reduce stress among students.[71] Recent neuroscience work has considered the states of the brain that are best suited to learning. For example, Yoo et al. show that there are specific brain states in which a student is likely to learn well, and other specific states in which the learner does not learn well.[72]

While this result is intriguing, it does not explain how to get the brain to the good state. A subsequent paper suggests one way to reliably push students into good states for learning: make them curious.[73] Using functional magnetic resonance imaging, the authors show that curiosity can cause anticipatory activity in the midbrain and connect it functionally to the hippocampus. This may be the mechanism underlying the Socratic dictum, "wonder is the beginning of wisdom."

Retrieval practice, also called the testing effect, is a now a well-established technique to enhance learning. In short, students who are required to recall recently learned information are more likely to retain it than students who are not.[74,75] The approach of engaging repeatedly in recall activities is called interpolated testing. The thoughtful design of retrieval questions is crucial, as recalling less important facts may cause more important aspects to be suppressed.[76] Retrieval benefits also appear to transfer across knowledge domains — the learning from retrieval practice may not be limited simply to factual memory.[77]

Furthermore, students often have misplaced confidence in their understanding of material, and thus have difficulty calibrating their perceived ability with reality.[78,79] Retrieval practice, especially in the form of interpolated testing, can help calibrate the learner.

A conventional approach is to give students a block of practice right after they have learned a topic—in the form of a problem set, for example—and then to revisit the topic only much later during a high-stakes final exam. Extensive research from cognitive psychology, dating back at least 100 years, shows that spaced learning and retrieval is more powerful than blocked practice for long-term recall even if it may not be as effective for immediate regurgitation.[80,81,82] There has also been much work on the topic of the optimal spacing of practice for retention.[83]

Bjork and Bjork also draw a contrast between storage strength and retrieval strength. They argue that current retrieval strength can create an illusion of long-term storage strength and competency.[84] To combat this, they introduce the concept of desirable difficulties – spacing and interleaving combined with other features which increase the depth of processing, and slow down learning, such as changing the setting of learning and even introducing a difficult to read font. In addition to retrieval practice, spaced retrieval and interleaved practice, they discuss the advantages of the generation effect: asking learners to anticipate or create new knowledge creates deeper learning than does simply looking up new information.[85] Many teachers model this practice in their classes, opening up the class with a challenge that the students will learn about. Reasonable questions following from this approach are whether generation of answers can help learning even if they are wrong, and whether feedback is effective even if it is corrective. In other words, is it better to have made a mistake and been corrected than to have been guided unerringly to the correct answer? The evidence seems to be "yes" to each question.[86] Moreover a form of rich feedback called cognitive feedback has been shown to be useful when the subject is learning about uncertain situations.[87] However, cognitive feedback requires judgment and tailoring which seems best supported by a human coach; automated systems are not yet capable of matching human performance in this area.

How much "hand-holding" does a novice learner need, and should she be encouraged to learn by pure discovery? Cognitive load theory (CLT), which posits an architecture in which the brain has a limited ability to process new information because of limits to working memory, provides a framework for addressing this question. The key to learning new information in CLT is the "compression" of that information, using schema that the student has at her disposal from earlier learning.[88] The more advanced and diverse the set of schema, the more able the student is to "digest" new information. Therefore, for novices with limited schema, the focus should be on building those schema. For this reason, CLT suggests—and the evidence supports—the idea that novices should be given worked examples rather than open-ended problems.[89] However, for experts open-ended problems work better, because experts have more advanced schema at their disposal.[90]

Cognitive scientists are also exploring the impact of context, intent, and physical interaction on learning. In order to encourage students to develop useful proficiencies, it appears important that the context of the learning reflect the context in which that information will likely be used.[91] So, for example, a student who learns about welding in the context of creating an automobile, and better yet, who receives a tour of an auto factory, is more likely to recall the lesson when she later works in a factory than a student who learns to weld without context. The connection of this research with situated cognition (above) is another area in which cognitive science research connects with learning sciences. Research also suggests that intent makes a difference: students who were shown videos on how to assemble a toy performed better if told that they would later be given the opportunity to assemble the toy than did students who were not provided the intent.[92] A final example shows the benefit of physical interaction; students learning angular momentum who were given the opportunity to handle a spinning bicycle wheel (where they could feel the gyroscopic effect) learned better than students who did not experience the physical manifestation of changing angular momentum as torque.[93]

Neuroscience

While cognitive psychologists consider learning at the level of the brain, neuroscientists consider it at the level of the neuron and structures in the brain. Neuroscientists have made significant strides in understanding the workings of the brain over the last decades, starting primarily with key stages in memory formation: initial encoding, followed by integration of memories with other memories, and then processes called consolidation at the synaptic and system levels. Sleep is thought to play an important part in these processes,[94] which occur on time scales ranging from hours to days to months and perhaps years.

Recent findings in this area appear consistent, in an inside-out manner, with retrieval learning, spaced learning, and cognitive load theory. For example, blocked learning may be associated with saturation at the synapse during a process known as long-term potentiation, while spaced learning enables recruitment of "missed synapses" and allows better long-term retention.[95]

The brain function associated with the testing effect, as opposed to restudy, has also been mapped using fMRI.[96] Learning by testing (retrieval) has also been correlated with deeper cognitive processing.[97] Similarly, cognitive load has been shown to be measurable using pupillary dilation, suggesting a deeper implication on the brain and attentional focus.[98] The embodied cognition experiments of Kontra et al.[93] hypothesized that activation of sensorimotor brain regions would enhance understanding of torque and angular momentum. fMRI imaging showed that more active training methods correlated not only with better test performance but also with greater stimulation of the predicted brain regions.

As neuroscientists provide possible explanations for the observations of cognitive psychologists through experiments like these, and cognitive psychologists explore learning on the level of the individual and her thought processes, the best practices in education become more deeply understood.

Discipline-Based Education Research

Individual disciplines, especially STEM disciplines, have long wrestled to identify the best ways to explain topics within their domain. Physics has been an exemplar in this area. The design of curricula by leading physicists goes at least a century. For example, Millikan published a reform physics curriculum in 1903 that integrated learning with laboratory work.[99] Feynman's Lectures, in which he laid out pathways from basic physics concepts and mathematical techniques to complex and powerful theories, remain a classic example of educational innovation built from within the discipline.[100] The Physical Science Study Curriculum, developed for high school students in the 1960s by a committee of prominent physicists led by MIT's Jerrold Zacharias, combined theories, concepts, and experiments in a novel and influential way.

But by the mid-1970s physics educators were transitioning from a focus on curricular design to a deeper consideration of how the cognitive and social factors we have discussed influence the learning of physics. McDermott's work at the University of Washington[101] and Hestene's[102] at the Arizona State University provide early examples—much of it emphasizing the identification of conceptual rather than mathematical difficulties students encounter. Tinker at TERC, working with students as early as middle school students, and Thornton and colleagues at Tufts, primarily for first-year college courses,[103] introduced laboratory hardware into this equation. They pioneered the use of sensors connected to microcomputers to collect data from classic physics experiments and present it in graphical form; students showed improvements in both physical understanding and mathematical communication (graphing skills).[104]

Hestene's Force Concept Inventory (FCI),[105] a standardized test of physical concepts introduced in 1992, played a key role in convincing the physics community that understanding these difficulties was essential to good teaching. The FCI also became an important assessment tool; as physics education research developed into a distinct area of scholarship; many researchers used the FCI to evaluate the efficacy of new instructional methods. The inquiry and discovery-based physics programs discussed earlier (see p. 7) have been validated by this and similar assessment methods. McDermott's Physics Education Group has, more recently, also developed active learning approaches tailored to the needs of pre-service K-12 science teachers.

Over the years, the formalization of physics education as a science in and of itself has gathered momentum and support.[106] In the process, educators in other STEM disciplines have adopted physicists' pedagogical advances. In areas such as biology[107] and chemistry,[108] educators have also followed suit in exploring the pedagogy of their own discipline, researching questions about student learning and understanding specific to their own knowledge domain.

The importance of disciplinary thinking and domain-centered communities in education received a major affirmation with the National Research Council's Discipline-Based Education Research report.[109] Chapter 2 of that study presents a detailed review of the DBER literature in physics, chemistry, engineering, biology, the geosciences, and astronomy. In addition to presenting a history of DBER across disciplines, the report considers a number of topics within particular disciplines including conceptual understanding, curriculum, problem solving, assessment, and attitudes. A companion publication was recently produced to translate the findings into guidance for practitioners.[110] A basic idea is that experts from the disciplines with knowledge of pedagogy could bring a new level of nuance to the discussion on education—and complement education experts from outside the discipline.[111]

A recently published synthesis of physics education research, developed from material commissioned for the NRC DBER report, is targeted at physics educators but includes insights and reflections which may inform education researchers in other disciplines.[112]

Another insight from DBER work is that fundamentally different forms of curriculum development may be appropriate for different fields. Expertise in different fields may require different

Publishing DBER Research

The emergence of new journals speciallizing in research related to teaching and learning in a particular discipline is an indicator of the maturation of fields within DBER, providing valued places for disciplinary researchers to publish their results and structure for their communities.

Examples of DBER journals include:

- CBE- Life Sciences Education
- Chemistry Education Research and Practice
- Physical Review Physics Education Research
- Journal of Engineering Education
- Journal of Geoscience Education
- International Journal of Research in Undergraduate Mathematics Education

As these journals have helped bring legitimacy to DBER studies, traditional science education journals such as the American Journal of Physics, the Journal of Chemical Education, and the Journal of Research on Science Teaching— in which some of the foundational DBER research appeared—have created special issues or sections to highlight education research studies. Cross-disciplinary journals such as Science and Nature also now include DBER studies among their general interest articles.

mental models and different approaches to curriculum development. Cognitive task analysis (CTA) is a set of techniques for identifying and structuring the models, rules and intuitions that experts bring to bear in the practice of a discipline.[113] The important role of subject matter experts in developing content with CTA confirms the strategic value of engaging disciplinary experts early in learning design. Experts are also able to identify the root causes of student misconceptions and preempt them by considering the correct and incorrect mental models that lead to misconceptions.[114]

Social Science Perspectives on Education

Social scientists have studied education in its entirety, and many particular aspects including online learning. Virtual ethnographers have explored how users interact with technology. They describe virtual cultures in ways that inform interventions and designs.[115,116,117] The development of a better understanding of how users currently live, learn, and interact in virtual spaces can help researchers and designers consider how to address socio-technical problems.[118] In particular, social scientists have begun to explore issues related to race[119,120] and gender[121,122,123] in online spaces, often beginning with game worlds. Similarly, demographers and sociologists have highlighted barriers to success and have worked with demographic data to improve understanding of access, utilization, and success; for example, research shows possible wealth disparities between users and nonusers of online resources.[124] In a recent publication, Shanna Smith Jaggars explains that understanding when and why users choose online platforms to learn is crucial to designing effective online learning environments. Understanding who users are and what subjects they choose to learn online is also essential.[125] One significant area of research amongst the social sciences is how people interact, communicate, and form communities. Some of this research pertains to social forums or special interest groups[126,127] while more recent research investigates who participates and how in online course forums.[128,129,130] Further extensions of this research investigate the formation of ***meetups*** associated with online courses, and the organization and outcomes associated with these events.

Other researchers have raised questions about how various demographic groups may be helped or hindered by the expansion of online learning, contributing to the broader conversation on the digital divide.[131,132,133,134] In particular, several sets of skills have been identified that students will need to succeed in the context of new spaces and new media.[135] A variety of researchers have studied the use of online learning as a tool to expand access to education in rural and small schools.[136,137]

Much has been written about the impact of online education on the unbundling of education.[138] Private online colleges such as the University of Phoenix have drawn the attention of the public and of government regulators.[139] This has led to soul searching about the value of higher education and its "return on investment." Discussions about online education will likely remain intertwined with discussions about the cost and value of education for the foreseeable future. Economic analysis can frame this increasingly important debate. A number of economists have focused on understanding the socioeconomic impact of educational attainment. While arguments for the economic and political importance of education are not new,[140,141,142] economists have focused recently on the relationship between education and inequality.[143,144] For example, the "education race" model suggests that if the supply of educated workers does not keep pace with increasing demand for skills, the wage premium for these skills will increase.[145] In a recently published study by David Autor, workers in the United States received more than a 25% increase in wages for one standard deviation increase in skill as measured by test scores, the highest measured return to skill among the group of nations examined.[146] Years of schooling have been found to be moderately correlated with numeracy skills and also to be a substantial and significant predictor of earnings.[147] Economists have traced this model through the 20th and early-21st centuries, explaining various changes in both the supply of and demand for educated workers.

A reasonable conclusion to draw from these studies is that an increase in the rate of growth in educational attainment should lead to a corresponding decrease in earnings inequality. Despite rising tuition costs, a variety of studies have emphasized how college remains a very good investment.[148] Economists will need to play a leadership role in valuing online education and other educational innovations, including their potential impacts on access to and costs of higher education.

Recently social scientists have taken a more design-focused approach to understanding learning online. Researchers in Human-Computer Interaction—merging behavioral science, computer science, and design theory— have developed principles for improving the design of online communities, focusing on important factors like recruitment, contribution, and behavior.[149] Others have explored the impact of real-world culture on utilization and success of technology, highlighting roadblocks to the transfer of technology between cultures.

Education Technology

Technology has long impacted education. There are several publications dedicated to the field of "edtech." Again, it is difficult to do justice to the entire topic in this report, but we describe a few key trends.

Distance education has existed in the United States in various forms for more than a hundred years. It has progressed in waves with the expansion of new technologies, from written "correspondence courses" to radio and telephone, from TV to video over the Internet.[150] Education is an early target application for many innovators, so the history of technology-supported education is almost as old as the technologies themselves. With the advent of each new technology comes predictions of fundamental changes in education. Yet few of these changes have been realized. Digital learning may indeed be the technology that breaks that pattern, but this will only come to pass if we bring together what we know from the disparate fields discussed here.

The concept of automated teaching dates back at least to the mid-1950s, the era of Skinner's Teaching Machine,[151] a device based upon behaviorist training principles to reward or punish learners for corresponding positive or negative responses. Despite the methodological shortcomings of Skinner's approach and its questionable underlying principles, many current automated learning systems still reflect this design. Later in that decade comes the invention of Plato,[152] a more sophisticated online learning environment that predates the era of personal computers. In the early 1960s, Papert came to MIT and began working on technology-assisted implementations of his constructionist approach to learning. In 1967, Papert and colleagues at Bolt, Beranek, and Newman, introduced the Logo programming language to help students learn mathematics and programming concepts. The famous Logo-driven Turtle robots first appeared two years later, and variants persist to this day.[153]

Intelligent tutors started to be popularized as work in both human cognition and artificial intelligence advanced in the 1970s and 1980s, beginning with the work of Anderson[154] et al. at Carnegie Mellon University, which introduced the cognitive tutor. The Open Learning Initiative (OLI) at CMU further developed the use of mini-tutors into an extensive outside-facing course, initially in statistics, which was implemented to impressive result.[155] As personal computers entered the classroom in the 1980s and 1990s educational games found a place in the learning market. Titles such as the CD–ROM-based Oregon Trail (MECC 1971—first developed on a mainframe and then on PCs) utilized computers to provide students with individual simulated experiences that they were previously unable to get. Educational games continue to be an important area of digital learning. Today, research and development in educational games embody important principles such as collaborative learning, scaffolding, and socially constructed knowledge.

As Internet access became pervasive, online learning started to become a reality. Many universities and both for-profit and not-for-profit companies created online learning programs. MIT's OpenCourseWare (OCW) initiative helped jumpstart the open-access movement in 2002, leading to the widespread Open Education Resources (OER) movement.[156] Inspired in part by OCW, Salman Khan launched the "Khan Style video" micro-lectures in 2006. Many of these efforts were intended to facilitate distance education, though Khan encouraged schools to use his material to flip their classrooms. The University of Athabasca and the Canadian Government's National Research Council coined the term "MOOC" for the first "connectivist" MOOC launched in 2008; in connectivist MOOCs the class is more participatory and the teaching is more decentralized.[157] The first "xMOOC," which refers to the prevalent MOOC style today in which a single site is the source for the content, the forum, and the assessments, was Stanford University's "Introduction to AI" in 2011. In 2012 Coursera and Udacity were formed as private companies to provide MOOCs, and MIT and Harvard University jointly launched the non-profit edX. These MOOC "platforms" post and offer courses developed by their large groups of participating universities. edX also open-sourced its software in 2013, enabling entities across the world to download the edX code and run local instances for the purposes of local blended learning. MIT has run more than 90 courses in blended format on campus and on edX at the time of this writing.

Games researchers are capitalizing on this data-intensive approach, and have also contributed more approach-specific design principles, exploring the impact of game mechanics on motivation, retention, self-efficacy, and other related metrics.[158,159,160,161] Two new key trends are emerging. The first is mobile gaming,[162,163] and the related field of augmented reality, which combines place with information on the mobile.[164] Virtual reality is a second trend.[165] Though completely virtual and interactive learning environments are not yet broadly ready for consumer use, the availability of products such as the Oculus Rift may provide a further impetus to this field.

There has been much work over the past few decades on the use of interactive simulations in learning.[166,167] This work has gathered pace in the last few years with organizations dedicated to developing and maintaining simulations such as PhET[168] at the University of Colorado and Mathlets at MIT.[169] The

Digital Humanities movement is a step in the same direction for humanistic education, although the type of interaction and simulation is different.[170,171]

Finally, the possibility of labs-at-a-distance, where a student in a faraway setting can manipulate a real lab through a virtual interface, is an idea that has received some attention, and may be especially important for equipment that is expensive or highly specialized.[172]

Assessment

Assessment in its many forms is a key to many modern efforts to improve education, and is becoming important in the context of online education. Students, teachers, institutions, curricular materials, delivery methods, and interventions can all be assessed, on varying timescales and to various ends. All modalities of assessment rely on related concepts such as statistics, psychometrics, cognitive task analysis and design. We argue that this field deserves separate mention and will become more central in the years ahead, with online and developing technologies offering new opportunities to perform and utilize assessments.

Student Assessment may be short, medium or long term.[173] Assessment of student learning in the short term is usually formative (i.e., monitoring progress to help students and teachers fine tune their learning strategy) and should involve appropriate delivery of feedback to the student. Medium-term assessment may be more summative, measuring how well the student has learned a set of material collected as a course or curricular module. Long-term, or longitudinal assessment, monitors how well the student has retained, integrated, transferred and applied knowledge, skills and attitudes (often from multiple courses) in order to further his or her life goals. Longitudinal assessment is difficult to perform, and there is relatively little work on long-term educational assessments apart from consideration (often by economists) of group outcomes.[174]

In its traditional forms, student assessment is an inexact science of inferring the learner's level of understanding from a few questions and answers. In principle this should entail evaluation of test materials in terms of cognitive models, tasks the acquired knowledge should enable, competencies the student must show, and the inferences that can be drawn from the evidence gathered. The work of Messick in the 1980s and '90s defined key issues in the field, helping to define the modern concept of test validity and emphasizing the need to consider the social consequences of testing itself.[175] Since then there has been a great deal of work on assessment. Evidence-Centered Assessment Design (ECD) has proven useful and become a well-accepted framework for short and medium term studies.[176] Its application to formative assessment, in a manner that recalls retrieval practice, has shown benefits.[177] For more in-depth descriptions, see comprehensive texts on testing such as Downing and Haladyna.[178]

Online, assessments were initially limited to multiple choice questions. But as we have discussed earlier, advances in machine grading are making them more elaborate and insightful. Even multiple choice tests can be richer in the online environment than on paper—in the standard edX model, for example, learners get two or more chances to choose the right answer, with instant feedback. Computer programs, drawings, circuits, writing samples, and other artifacts can now be automatically analyzed and graded, providing deeper insights into student understanding. Used in conjunction with strategies such as spaced learning, online tools offer new opportunities to introduce formative components to medium- and long-term assessments.

Statistical models are needed within a framework such as ECD (and independently) to model both student and test. The classical approach here is item-response theory, developed more than 40 years ago. It continues to have a central role in calibrating tests and students with each other, especially with the large population samples provided by MOOCs.[179] Statisticians from the field of neuroscience are developing alternative models of learning which may soon find applicability in assessments as well.[180] In the years ahead, big data and machine learning may give us further tools for understanding student abilities and calibrating test problems across abilities. While the issues Messick identified will not disappear, combining classical methods with new insights and the availability of fine-grained information on each student's activity may significantly alter the balance between evidence and consequence.

Evaluation of the system for delivering learning, or ***Learning System Assessment***, is another aspect of assessment. Again there are three scales: small (tests and individual questions), medium (courses and texts), and large (programs and institutions).

At the smallest scale, tests and problems need to be analyzed and calibrated for their difficulty and their power of discrimination -- how precisely do they dissect a population of students into those who understand a concept and those who don't? Here, too, item-response theory and similar techniques are commonly used.

A large body of work addresses exists on medium-scale evaluation,[181] with quality, standards and accreditation playing important roles. We will focus here on assessments of online courses. Several authors have reviewed the efficacy of certain implementations of online education, but because of the logistical difficulties of testing and the problems inherent with comparing fundamentally different implementations of technology, only a few are comprehensive in their treatment and they are inconclusive.

The U.S. Department of Education published a meta-analysis in 2009.[182] Figlio et al. critique this study, and provide the results of a randomized trial with 325 student volunteers.[183] Their findings modestly favor "in person" learning over online learning. Bowen et al. conducted a larger randomized experiment comparing students who studied statistics in the traditional way with students who studied it online.[184] To quote the authors, "We are persuaded that well-designed interactive systems have the potential to achieve at least equivalent educational outcomes while opening up the possibility of saving significant resources which could then be redeployed more productively."

Bowen et al. rightly caution that much work remains to be done. There are many different implementations of and contexts for online learning, and there are questions of whether today's MOOCs use best practices, how they can be improved, and which approaches best fit different fields of study or populations of learners. A study examining 76 MOOCs found that while most were well organized and presented material clearly, they paid little attention to established principles of instructional design (assessed by compliance with an augmented version of Merrill's First Principles of Instruction).[185,186] This underscores the opportunity and the challenge ahead: online technology must be deployed with careful consideration of pedagogy. We should avoid the tendency, in taking on this challenge, to think of, design, and evaluate MOOCs as online counterparts to traditional courses. This, Butin notes, undercuts many of their core strengths.[187]

As with student assessment, large-scale assessment of programs remains difficult and infrequent. In principle one would like to ask several questions. Do students who complete this program succeed in the long term? Is the content appropriate for their personal or professional success? Are they able to retain the knowledge and skills they acquire, and apply them in work settings? Perhaps one day questions like these will become easier to answer with longitudinal data obtained through interviews or analysis of publicly available career data from sources such as LinkedIn profiles.

The scale of MOOCs and the advancements in our understanding of data science have brought new opportunities in educational assessment at every scale. Online activities generate vast quantities of qualitative data (e.g., responses in forums), quantifiable responses (e.g., quiz answers), and trackable data (e.g., click streams from usage of online materials). There is significant research effort in performing post hoc analysis on these data to understand what students are doing online.[188] Accompanying A/B testing[189] research can contrast the efficacy of different media, presentations or activities. Designers are beginning to use this data to detect learning challenges for individual students and route them to appropriate resources. This data is also being summarized and provided to teachers to gain insights into their students' understandings, and there are many opportunities for research in this area to contribute to continuous improvement of online platforms, tools, and offerings.[190]

Other Contributing Fields

It is impossible to list all the fields that impact education in the space of this report. Our effort here has been to show that there are many fields that appear to have a significant bearing on education, fully recognizing that this list will continue to grow. Here we list a few other areas that we believe are relevant from the perspective of this report.

One area that has received considerable attention is motivation and rewards in learning.[191,192] Although focused on primary and secondary education, the work of Dweck[193] on learning versus performance measures and on a growth mindset has been influential in the field of education. This connects to the cognitive psychology work listed earlier and also fits with research in educational games—many educational games already embody a deep understanding of the factors that draw users to a game and keep them playing.[194] Student completion rates have recently attracted a great deal of attention. Carefully orchestrated motivational approaches, combined with community and interdisciplinary engagement, appear to be successful in helping students overcome factors like low confidence that are correlated with socioeconomic status and ethnicity. They should be incorporated in programs that use online educational technologies to reach underserved populations,[195] building on successful approaches used in residential settings at places like the University of Maryland-Baltimore County and the University of Texas-El Paso.

Health and nutrition is a second area known to have long-term impacts on education outcomes.[196] As an example, the work of Kvalswvig et al. explores the negative impact of the whipworm parasite *trichiris trichiura* on cognitive development.[197] Related work has shown that the treatment of that parasite results in improvement of cognitive function.[198] Pollitt describes how iron deficiency can have a (reversible) impact on cognitive function, especially due to impact on the iron-dependent dopamine D2 receptors in the cortex.[199] Similarly, child health has been shown to have a long-term impact on school enrollment.[200] The possibility of selective distribution of nutrients within a family further complicates the discussion, introducing possible gender disparity in long-term performance.[201] While this research has largely focused on primary and secondary education, implications on higher education are worthy of research.

A third topic is the architecture and design of learning spaces. The MIT Institute-Wide Task Force on the Future of Education at MIT recommended a rethinking of spaces at MIT to better support blended learning. Figure 3 shows the TEAL classroom at MIT; many universities are adopting

Figure 3: Technology Enhanced Active Learning classroom at MIT

Courtesy of Mark Bessette
MIT Center for Educational Computing Initiatives

similar models. Much recent literature has focused on the roles of formal and informal learning spaces,[2022,2033] whether physical in form, virtual, or a blend of the two.[2054,2065] New spaces should facilitate social interaction, individual reflection, discussion, and project work. Maker spaces, which facilitate types of learning that are currently best implemented in residential settings, become more relevant as well.[2076] Formalized design processes, seeking to understand existing space and space utilization, student workload, and learning processes, will facilitate effective design of these spaces.[2087]

A fourth topic is the necessary mix of cognitive, social, and intrapersonal skills needed for life and work in the modern era. A recent National Academies study examines evidence that non-cognitive skills are not independent of the knowledge domain in which they are learned, and —much like cognitive skills —must be more deeply mastered before they can be readily applied in new domains, or transferred.[2088]

4. BRIDGING FIELDS

There are clearly many connections, some established, others incipient, and some speculative, across the different fields impacting education. The trade-offs are many, and much experimentation remains to be done; Koedinger et al.[209] lay out the trade-offs systematically. We highlight a few connections and gaps on the following pages.

Connections Across Fields

While part of the focus of this report is to discuss the potential for stronger connections between fields of research in learning and the likely benefits of such connections, existing connections and collaborations have already produced valuable and interesting results.

- The generation effect[210] – where asking learners to anticipate or create new knowledge creates deeper learning – may describe an underlying mechanism that supports constructivist learning theories, and especially project-based learning. Projects encourage a wide range of good practices identified in cognitive science: First, they provide context; second, projects provide retrieval learning, spaced retrieval, and interleaved learning opportunities; third, they provide memorable retrieval cues. In the context of Chi et al.'s ICAP framework, the generation effect can be identified with "constructive" activities. Blended learning enables more time for such activities.
- There is a body of work indicating that depth of processing impacts the strength of learning.[211] While the precise measures of "depth," and the causes for this effect, are still debated,[212] the implications of the broader concept are important in education: how does one encourage thinking, processing, and deep learning? Deep learning (i.e., engaged learning that results in mastery of concepts so they can be transferred and applied to new situations) should draw upon both cognitive science and education research. Cognitive science can guide conceptual acquisition and memory of concepts, while education research guides the design of contextualized activities that promote engagement, transfer, and application to novel problems. Early indications are that online tools can also support deep learning.[213]
- Mind wandering will likely be an important domain in learning research, especially given concerns about the ability of students to focus in passive lectures. Furthermore, research findings on mind wandering are immediately applicable in online learning. MIT and edX researchers show that the ideal length of videos is about 10 minutes.[214] Despite this potential, research in mind wandering and online education has been linked only very recently. Meanwhile, research in neuroscience is casting light on

the mechanisms of mind wandering, and even identifying positive outcomes of the process such as creativity and spontaneity.

- How important is "hands-on" activity? Here too, emerging connections between the classroom evidence of education researchers and the findings of cognitive scientists can be better leveraged. Educators have long maintained that hands-on activity is essential—in fact it is a founding principle of MIT. A recent study shows remarkable gains among participants in a MOOC when watching and reading is bolstered with "doing" interactive online activities.[215] Cognitive psychologists are now clearly seeing this effect in well controlled experiments. For example, the work of Kontra et al. and Frey et al.[216] begins to show that physical experimentation, or even the intent of hands-on activities, may impact learning. There is a wider connection to be made, regarding the most beneficial type of hands-on activity. For example, there is evidence that hand writing notes is more effective than taking notes on a computer.[217] Similarly, designers perform better when they use hand sketching in the early stages of design than when they use CAD.[218] These illustrate the idea, broadly known as embodied cognition, that a person can best represent concepts when they are closely sensing or manipulating the related artifacts. This has been demonstrated across the spectrum of age groups.[219] Collectively, these results shed light on the importance of blended learning. Online learning can help create the time for hands-on activities, hands-on activities are essential, and whenever possible should not be replaced by online tools.

- Retrieval practice, an approach long espoused by cognitive psychologists, can be readily applied in online learning; short videos followed by immediate assessments are an implicit application of retrieval learning. Spaced retrieval has found application in commercial software packages such as SuperMemo[220] and DuoLingo.[221] However, despite promising results from the field,[222] this technique has not been well tested or widely applied in education practice. To the extent that this results from the difficulty of implementing retrieval learning in a traditional classroom, newly available technology may speed its adoption. Spaced practice and interleaved practice can be applied to online learning and can more easily be implemented in face-to-face environments with the help of well-designed supportive technologies. This approach has the additional benefits of reducing mind-wandering and encouraging mastery learning.

- Research in neuroscience on curiosity, supporting the ancient Greek proverb that wonder is the beginning of wisdom, neatly complements theories on motivation and engagement. This research also complements work from cognitive psychology showing that curiosity improves retention.[223] This early-stage work is beginning to connect outside-in theories with inside-out thinking, and also to explain the importance of material presentation, inspiration, and context. These insights can help us better use both online tools and in-person interactions to achieve the right environment for learning.

- Cognitive-load theory and other insights from cognitive psychologists help explain the benefits of approaches such as task-centered instruction and deliberate practice.[224] The basic idea is that by providing scaffolding in the early phases of learning, we can gradually build students' schema to the point where they can engage in freeform projects. Just-in-time learning can play an important part in such approaches, and is also enabled by online learning in a blended approach.[225]

- Ideas related to rich cognitive feedback may serve to inform the role of the educator in face-to-face learning. In addition to designing task-centered instruction and project-based learning, the teacher can play a key role in providing cognitive feedback to students—helping not only with the material at hand, but also with the metacognition needed to truly master learning.[226] Here we see the invaluable input of teachers that online tools struggle to match. Furthermore, teachers may be able to facilitate integration of knowledge, transfer to new scenarios[227] and the ability to perform authentic tasks.

- The connections between cognitive task analysis, rich cognitive feedback and task-centered instruction are also promising avenues for research. The importance of understanding how the experts think, how to extract implicit and declarative aspects of their expertise, how to form tasks that mimic more authentic applications, how to ensure integration and transfer, and how to scaffold a student through the experience are together a challenging task for curriculum development and delivery. Achieving this task will likely require a new breed of educational professional – the "learning engineer" that we describe in the next section.

- Cognitive task analysis can help with creating a richer blended experience and can assist with student retention.[228] Non-cognitive interventions, delivered online, also offer promise in student retention.[229] The Texas Interdisciplinary Plan combines interdisciplinary education with smaller classes, more face-to-face contact and motivation to improve the performance of students.

- Discipline-based education research is intertwined with research in education more broadly. The physics and math simulations in PhET and Mathlets, for example, combine broad principles regarding the use of interactive simulations with deep knowledge of the fields of physics and mathematics. Disciplinary experts, working in concert with experts in the broader learning sciences, can create scaffolds and learning paths traversing knowledge within a discipline as well as core interdisciplinary concepts. Working in this way, DBER practitioners can learn from and contribute to a variety of other fields in the learning sciences. While DBER has developed within STEM fields, new pedagogical approaches in disciplines such as history can also be interwoven into this approach.[230]

- Communication, collaboration, and community formation are key elements to creating effective online learning environments. Social scientists can help us understand how to enhance these experiences online, but educational technologists must in turn apply that understanding to create more effective tools and practices. The kinds of collaboration and communities that are effective are likely dependent on the domain and content, so contributions from the DBER community will also be essential.

- Research on ethnography and demographics in online education can guide the design of effective online programs. Following the unsuccessful Udacity pilot with San Jose State University, we must recognize that online education cannot be seen as a panacea for social factors in learning.[231] Situated cognition, with its emphasis on reformulating learning to suit the local social context, may be pertinent in this situation. Connections are also emerging between social context and neuroscience. For example, Anderson et al. have found a correlation between students' economic statuses and cortical grey matter volume in the brain.[232] Connections between health and nutrition, early childhood development, social conditions, and the income-achievement gap have the potential to inform research and development in the years to come.

- As post-secondary education unbundles, continuing education for degreed students is becoming an important avenue for maintaining a skilled, globally competitive workforce. Continuing education is especially relevant in fields where the pace of innovation is rapid. Working professionals in many fields, such as programming or medicine, must keep up not just with technical advances, but also with new business models, regulations and work-practices. Middle-skills workers with associate's degrees must also keep up, not only with new technologies, but also with advancing business practices. Online education can play an important role in this emerging world. Many of the topics discussed in this report apply equally well to continuing education and coursework towards a degree.

- The "big data" from online learning, especially from MOOCs, can be mined for connections across fields. MIT and Harvard have conducted detailed joint analyses of the first two years of their courses on edX.[233,234] Such research has uncovered much about the demographics of edX learners: among the students registered from the fall of 2012 through the summer of 2013, the median age of an MITx or HarvardX student was 26, 29% were self-reported as female, 33% had a high school education or lower, and 6.3% were 50 or older. These numbers were based on a large population: 841,687 registrations from 597,692 unique enrollees. These data identify both the opportunities and the challenges of online education. Should courses be redesigned to be more adult oriented? Should courses be split to provide examples and tasks that are more suited to the demographic? The data may also identify course demand and sequence preferences. They may help us identify optimal module lengths and choices. Figure 4 shows results from the MITx/HarvardX Year 2 report on students who took multiple courses on edX. The results indicate how students transition from one course to another, they help us identify clusters of interest, and they show adjacencies of clusters.

- Finally, the opportunity to try out new ideas on platforms such as edX and to draw conclusions from them is a powerful new tool for advancing education. Whether at the CERN particle collider or at hospitals participating in clinical trials, science advances through experimentation. Online technology provides an unparalleled opportunity to experiment with myriad principles and ideas that are emerging across the education research landscape. As we try to implement research advances in practice, there will always be questions of parameterization, even for well-established principles like spaced learning. Some parameters will be tuned across the population, and some will be personalized to the individual (just as a video game calibrates its level to the user). MOOCs provide an opportunity to use randomized tests, unprecedented in both scale and flexibility, to tune results in the interests of learners. We believe this will be pivotal in bringing together principles from across fields.

Gaps

Insights from other fields offer enticing possibilities for improving educational practice, but these connections need to be weighed carefully before implementations are designed. Dunlosky et al.[235] provide an example with their in-depth look at transferrable insights from cognitive and educational psychology, laying out the research and experimentation that has already been conducted. In considering such connections, one encounters two kinds of gaps: knowledge gaps and process gaps. We are confident that knowledge gaps will be organically filled as a new consolidated research agenda is laid out—as has occurred in other areas such as energy, water, and cancer treatment.

Process gaps are more difficult to resolve. The field of education does not appear to have an integrated pipeline that promotes the transfer of concepts to reality. Intriguing as ideas from unfamiliar fields may be, it can be difficult to justify their implementation without strong experimental evidence to provide confidence that the value received will outweigh the cost. Experiments

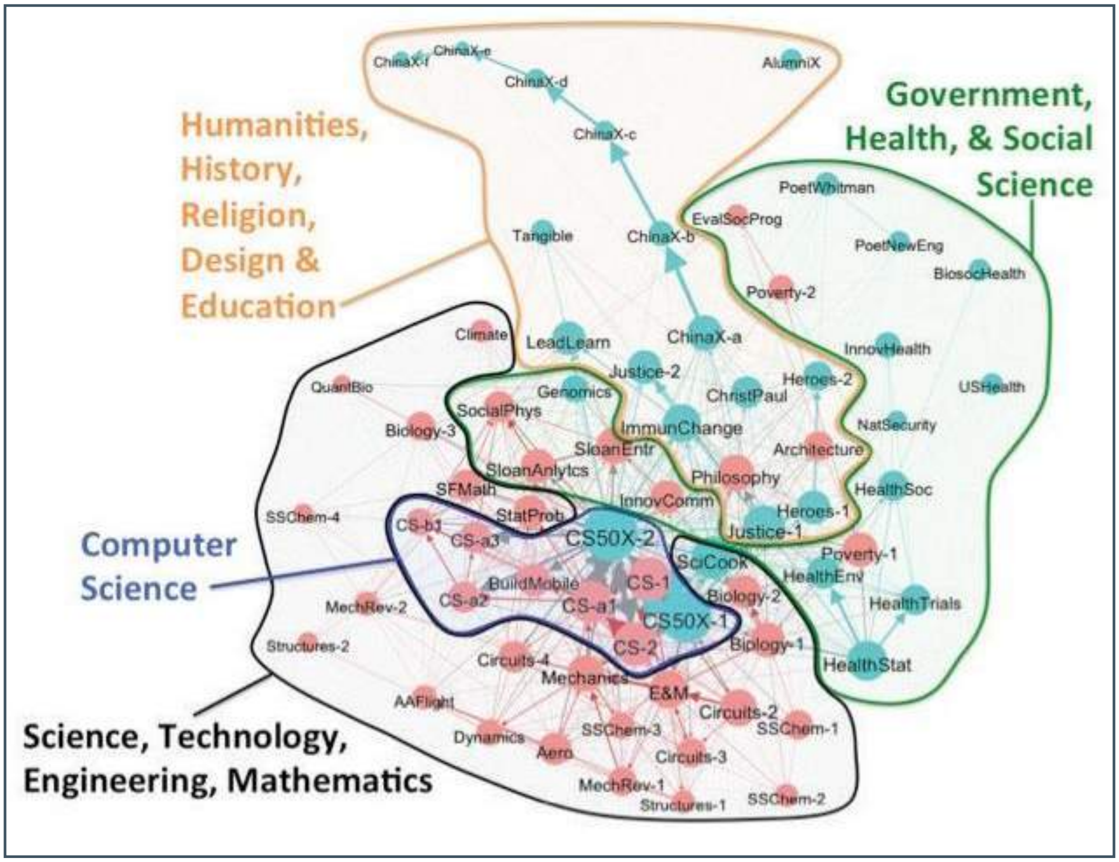

Figure 4: How students transitioned among MOOCs. A "big data" analysis of all MITx and HarvardX course participation shows student preferences and clusters. This can be valuable in designing multi-course programs.

Courtesy of Andrew Ho and Isaac Chuang

need to be realistic, whether in classrooms or in online settings. Unfortunately, a major gap exists here.

Cognitive psychologists often use artificial situations to model onsite or online classrooms. Perhaps for this reason, many promising ideas we have described have not diffused into education practice. On the other hand, education researchers can perform only limited experiments in real classrooms. In practice, few are pseudo-random, much less randomized.[236]

In Section 2, we discussed the inside-out and outside-in approaches to education research. Inside-out insights may work at the individual level, but may not yield success across real systems with heterogeneity across scales – that is, a fundamental understanding of the workings of one individual's brain may be inherently difficult to translate into interventions that are successful across a diverse population of learners. Similarly, outside-in insights, unless implemented, tested and scaled carefully, may also be limited in their impact. These challenges of transfer and scaling have resulted in a gap between fields, and even misunderstandings. Different questions clearly require different experimental methodologies. The design of these experimental methodologies is in itself an important challenge, yet it plays a critical role in scaling any practice or research finding from niche implementation to broader impact. The science of educational experiments is thus an important field of research in and of itself. Fortunately, thoughtful research has already begun on the topic, including the methodological challenges, difficulties of implementation, and pitfalls in interpretation.[237]

5. FINDINGS, OBSERVATIONS, AND RECOMMENDATIONS

We have described the complexity of the space we call education, and elements of a number of fields that affect it. We now make some observations and recommendations about how to address some of the complex challenges the community faces, in the context of opportunities afforded by the emergence of online education on a massive scale.

Recommendation 1: Increase Interdisciplinary Collaboration Across Fields of Research in Higher Education, Using an Integrated Research Agenda

The richness of research results across the many fields contributing to education—education research, DBER, social science, cognitive science, and others not discussed here—points to a pressing need for an integrated research agenda that increases coordination and communication among fields. This idea is not new.[238] We simply make a larger case that goes beyond the merger of cognitive science and education research.[239] We have given examples above where convergence between outside-in and inside-out approaches to learning research has produced valuable insights.

We have pointed to connections between cognitive science and education research, between social science and cognitive science, between social science and education, and so on. These connections highlight an opportunity to identify a research agenda for higher education that cuts across all these fields—while incorporating new emerging ones. By defining and beginning to execute such an agenda, we can form a more comprehensive, and, importantly, dynamic understanding of this important industry. The findings of such research could cast light on areas that are today debated, more and more controversially, based on ideology and opinion rather than knowledge. More systematic planning and integration could also help ensure that progress is targeted and deep rather than broad and thin.

One approach to encouraging collaboration would be to propose a grand challenge in learning sciences which many researchers from many fields might work together to address. But we hesitate to single out one problem among the many our systems of education face. We prefer a more comprehensive approach to collaboration and so have noted, throughout this report, a variety of opportunities for researchers from different fields to address related topics and work together on shared challenges.

There are steps that need to be taken. Funding agencies such as the National Science Foundation have made reference to similar themes over the last decade. What has been missing is a "man on the moon" meeting of minds. Universities and research institutions must challenge themselves to put together substantial, cross-school efforts which show commitment and agility in pursuit of the research problem. These efforts should seek out government and private funding sources including industry sources. The science of learning is surely as applicable in a corporate setting as it is in higher education. Funding agencies, meanwhile, must invest in such efforts on a large scale and hold both the funded entity and themselves to a high standard of scientific achievement, translational research and real impact. There is also a need for entities that will act as conveners, supporters and integrators. NSF and the Department of Education are the logical candidates for these roles, and their work could be buttressed by supporting foundations. Of course, there is also a need for testing, implementation and scaling of research findings that emerge from the process. The efforts discussed in Recommendation 4, "Institutional and Organizational Change" are very relevant at these stages.

While we make this recommendation in the context of higher education, it also has relevancy in preschool, elementary, and high-school (PK12) education and in continuing education of adults. The establishment of a new integrated research agenda could have a particularly steadying influence on PK12 practitioners, who complain of being subjected to changing fads and policies. The pendulum effect erodes credibility and adoption as top-down policies based on swinging trends buffet teachers in the field.[240] Our next two recommendations suggest focused mechanisms that could also promote deep interdisciplinary collaborations.

Recommendation 2: Promote Online as an Important Facilitator in Higher Education

Applying the findings of interdisciplinary research is a separate task from performing the research, and is perhaps more challenging. Consider cognitive science and education: there have been many pleas for applying the principles of the former to the practice of the latter, yet this remains uncommon. In a particularly trenchant article, Carnine claims that education, as a profession, has not truly accepted the value of empirical analysis.[241] We offer a different explanation: the uniqueness of each individual teacher, learner, classroom, and community make direct application of studies – which are limited in context – inherently complex and problematic. But this does not imply that study findings are irrelevant to real classrooms and real learning. Technology can support teachers in the application of the relevant principles across a group of students with high variability. In fact, technology can help tailor lessons to the situation in extremely powerful ways.

The instrumentation of the online learning environment to sense the student experience and the ability to customize content on a student-by-student basis may be the key to enabling teachers to provide differentiated instruction, informed by a solid foundation in cognitive science. Modern online courses and delivery platforms already implement some of these concepts, and provide a framework for others. We find that the following practices present significant opportunities for improving the learning experience:

- Typical video lectures used in online courses are short—on the order of minutes. This is consistent with recommendations from studies of cognitive load and mind wandering.
- In online courses, each video lecture or reading assignment is often followed by a formative test. This effectively implements retrieval learning and mastery learning. Interpolated testing further mitigates mind wandering.
- Different pathways can be established in an online course depending on whether a student succeeds at or fails a given test. This could facilitate mastery learning and differentiated instruction at scale.
- In an online course, it is possible to space out assessments so that a student is asked about a topic she covered several days, weeks or months ago. This is a form of spaced learning.
- Topics can be mixed more effectively in online settings, enabling interleaved learning. More generally online tools can keep track of, and adjust, desirable difficulties to match the capabilities of the student.
- Online tools can also offer graduated tasks of increasing complexity, challenging students to address more and more open-ended problems as the student's capabilities mature.

These learning components may seem at odds with the notions of active learning and constructivism espoused earlier in this report, but research clearly shows that there is a time and place for such instruction in the ecology of learning. Through integration with research from other disciplines, we can combine approaches to create truly great learning opportunities. For example, a challenging prompt grounded in a real problem may energize students and provide them with context, satisfying two principles of effective instruction. But those students still need learning resources to help them meet their challenge, and we can use online methodologies to provide those resources in the most effective way possible.

This suggests a synthesis of online and offline learning modalities and also of pedagogies. We refer to this as a ***dynamic digital scaffold***—a model for blended learning that leverages technology and online programs to help teachers improve instruction at scale by personalizing the students' learning experiences. Technology will not replace the unique contributions teachers make to education through their perception, judgment, creativity, expertise, situational awareness, and personality. But it can increase the scale at which they can operate effectively.

The challenge of piloting modern aircraft provides two important analogies to this model for blending online and face-to-face education. The first analogy is to fly-by-wire control systems, which bring together the best of modern sensors, digital control algorithms, and human pilots. The human pilot provides high-level inputs to control the aircraft's movements, while the computer control system responds to pilot commands and sensed environmental conditions to provide low-level inputs to the multitude of actuators on the aircraft control surfaces. The result is a complex feedback and control system that achieves performance, robustness, and reliability levels well beyond what a human pilot could achieve alone, while at the same time retaining the judgment, situational awareness, and creativity of the human pilot. This digital technology has now revolutionized modern civilian and military aircraft by exploiting the complementary skills and operating capabilities of humans and computers. It has made aircraft safer, more efficient, and ultimately accessible to more people. A dynamic digital scaffold can be seen as fly-by-wire for teachers. Online learning will not replace teachers, just as the fly-by-wire system has not replaced aircraft pilots. But just as a fly-by-wire aircraft control system enables a human pilot to operate her aircraft more effectively, through dynamic digital scaffolding a human teacher could effect differentiated instruction to a large number of students and achieve overall class learning objectives. Aided by technology, teachers can refocus their efforts on the aspects of learning that online tools cannot provide, including coaching and fostering reflection and creative thinking.

The second analogy from the aviation industry is to flight simulators, which have transformed the training of pilots in modern aviation. An online system with assessments and simulations, which give students instant feedback, can enable students to learn, practice, and internalize concepts outside the class. In aviation, the instructor is then able to focus on more advanced or complex tasks—such as dealing with bad weather, emergencies, and so on. The instructor is also critical in helping the learner reflect on their outcomes, apply them to new situations, and discuss them with their peers for mutual benefit. Similarly, in the blended classroom, the teacher will be able to engage in higher-value discussions with students.

The digital dynamic scaffold that we propose can be thought of as a next-generation cognitive tutor that builds on the work of Anderson et al.[242] We think of it as a "cognitive scheduler" which overlays online modules, tuning the experience to the individual student. This may provide the scientific basis for and engineering approach to something long sought-after but only vaguely articulated: personalized learning.

Recommendation 3: Support the Expanding Profession of the "Learning Engineer"

Formal education today focuses largely on the classroom. We believe that future educators will blend insights from the different fields described in this report—education research, cognitive science, disciplinary knowledge, social science, and so on—to offer each learner a carefully orchestrated experience blending online and face-to-face learning. The design and implementation of these experiences, based on science, will in our view be best carried out by a new breed of professional—the ***learning engineer***. We use this phrase as a shorthand to describe a person who might more comprehensively be described as a Learning Designer and Engineer.

The phrases "learning engineering" and "learning design"[243] have recently become popular. The term "learning engineering" comes from a 1967 piece written by the Nobel Laureate Herbert A. Simon. His definition of the role remains relevant today:

> The learning engineers would have several responsibilities. The most important is that, working in collaboration with members of the faculty whose interest they can excite, they design and redesign learning experiences in particular disciplines. [...] In particular, concrete demonstrations of increased learning effectiveness, on however small a scale initially, will be the most powerful means of persuading a faculty that a professional approach to their students' learning can be an exciting and challenging part of their lives.[244]

How does this differ from the modern-day profession of an instructional designer? In making the distinction, we follow the lead of several recent master's programs aimed at training learning engineers and designers. Here we focus particularly on the Learning, Design and Technology (LDT) program at the Stanford Graduate School of Education,[245] the Technology, Innovation, and Education (TIE) program at the Harvard Graduate School of Education,[246] and the Master's in Educational Technology and Applied Learning Science Program (METALS) program at Carnegie Mellon University.[247] Each of these programs has a basis in similar core principles—learning engineers must have a knowledge base in the learning sciences, familiarity with modern education technology, and an understanding of and practice with design principles. Preferably, they will also have a deep grounding in a specific discipline such as physics, biology, engineering, history, or music. An understanding of the contexts for education is also important, as learning engineers must understand the cultures and limitations of the environments in which they design. Learning engineers are not academic researchers, but they must be familiar with the language of several fields in the learning sciences in order to communicate with experts and stay up-to-date on current research. In addition to a foundation in theory, learning engineers should have experience working in the types of environments in which they will be needed, whether in schools, colleges, or edtech companies. The TIE program provides support for internships, and both other programs require extensive work with educators or designers.

Learning engineers will require a broad range of skills. They must be passionate about education, and must be aware of the latest research from at least several of the numerous fields of learning science. They must be *simpatico* with learners, and have good instincts for teaching. They must be prepared to work with teachers, administrators, and students. They must be prepared to support research and engage in continuous improvement based on rigorous expertise. They must be adept with technology and willing to leverage the latest tools in learning, including both open-source software such as Open edX and commercial products such as After Effects. They must be conversant in issues of accessibility and intellectual property rights. Most of all, however, they must be willing to commit a portion of their careers to this pursuit, and the nation needs to make it worth their while. Just as scientists and engineers are adept at experiments and statistics, learning engineers must be experts at assessment. Continuous improvement based on assessment must be a natural instinct, just as it is for the quality engineers at Toyota who continuously improve vehicle manufacturing.[248]

There are a number of ways in which these professionals could be trained. Analysis of early efforts has not determined the superiority of any single approach. Master's programs based on principles of learning engineering and design, while young, show much promise. There remains much work to be done in exploring different approaches and program structures. A larger community of programs, founded on the same general approach of synthesis and design as the programs described above but catering to varied contexts, would benefit both learning science and the practice of education.

An alternative to the master's program-based approach is the use of disciplinary specialists as learning designers within universities. Postdocs, for example, are already topical experts and may be familiar with DBER principles in their own area. They could be formally trained in principles of design and broader learning science. At MIT we now have 15 such disciplinary experts, all postdoctoral fellows or lecturers from disciplinary backgrounds. Each has most or all of the skills that we describe above. These "MITx Fellows" have already assisted faculty on a number of projects that are improving the quality of learning experiences for our students in online, face-to-face, and blended formats. While the formal training regime for these fellows is still evolving, the principle of recruiting and inspiring postdoctoral researchers to support learning design has received a largely positive reception from faculty at MIT. The expansion of this approach, however, would require substantial and broad support if learning engineering is to be established as a legitimate career path for PhDs. To become learning engineers, disciplinary experts need more formal training on educational topics, either during their PhD or after. They also need formal recognition, funding opportunities from a variety of sources, and broad institutional acceptance of the value they bring. DBER practitioners faced similar issues as their fields emerged over the last several decades.

As discussed above, these learning engineers help to resolve two larger issues in the learning sciences. First, they are encouraged by the nature of their positions to integrate research from a variety of domains in the learning sciences, and their training gives them an introduction to the research landscape in and language of these domains. Second, they provide a natural pipeline from research to practice by designing and re-designing learning experiences through a combination of rigorous design principles and insights from research. Learning engineers in isolation will not completely resolve either of these issues, but an expansion of the profession and the programs that support it would strongly benefit learning in a variety of contexts nationwide.

Recommendation 4: Foster Institutional and Organizational Change in Higher Education to Implement These Reforms

Higher education can be seen as a complex, established "legacy" sector of the economy.[249] Like other such sectors (energy, transport, manufacturing, or health care delivery, for example) it has over time "locked in" to technical-economic-social-political systems that are resistant to change.[250] In other words, higher education operates within an established system for its educational mission. It relies on established technologies such as textbooks and established delivery models such lectures, seminars, and laboratories. Its economic model is based on tuition for courses organized to fit semester time frames, with the completion of a designated set of courses required for conferral of a degree. It relies on social systems to provide its workforce—faculty and graduate students—through PhD programs organized by topical areas and not around teaching. This model has had political support, with states subsidizing public universities and community colleges and the federal government providing funding for student aid. State and federal authorities also largely control the accreditation of colleges and universities. None of these components is easy to alter. Yet learning-science-based online education (including the blended model) is disrupting the existing higher education teaching paradigm. Online innovations are changing or offering alternatives to a number of its features, including textbooks and lectures, the economics of tuition, competency assessment and credentialing, and faculty training for teaching.[251] The federal government is beginning an experimental program to provide financial support to students taking online courses from unaccredited providers.[252] Many systems and communities vested in the existing system will offer resistance to the disruptive innovation that online education technology is catalyzing.

Put another way, there are a series of barriers to entry at scale impeding innovators in legacy sectors such as higher education. What can we learn from organizational approaches that have been applied to introduce transformation in other legacy sectors? Could these fit into a higher education setting?

First, to state the obvious, the introduction of innovation requires the development of specific, sector-relevant ***innovations***. While progress in broadband access, mobile devices, computer gaming, and cloud computing have created great opportunities for educators, continuing innovation in learning sciences and learning engineering is clearly required if these general-purpose technologies are going to drive change and reform in the educational sector. Research and development in the learning sciences is needed to establish new best practices in higher education, including iterative assessment of both online and blended learning approaches. Support for discipline-based education research by the National Science Foundation, for cognitive neuroscience and related work at both the National Institutes of Health and NSF, and for educational experimentation and assessment at scale by the Department of Education, must continue and should be expanded, including an explicit focus on learning in online and blended settings. But research and development alone, and the innovations it stimulates, will not be enough.

A second prerequisite for change in legacy sectors is the creation of ***thinking communities*** which champion innovation. In education, a thinking community is needed to develop evidence-based practices for implementing research results. Implementation mechanisms—including propagation and scaling—must be supported and evaluation metrics for online learning must be defined. Reform-based thinking communities have disseminated the results of discipline-based education researchers in a number of STEM fields, including physics, biology, chemistry, engineering, and mathematics[253] and offer promising models within the educational community. But a thinking community for online education reform must operate not only within disciplines but also within institutions and research agencies. The work of Bryk et al. on improvement communities bears particular mention here.[254]

Third, ***change agents*** are needed within interested higher education institutions to lead the actual design, development, and implementation of the innovations in local settings. Communities require leadership. No single "agent" will be enough. The "lonely champion" model generally leads to isolating the innovation and preventing it from scaling; a core team must be built around change implementation to build mass and seek additional faculty buy-in. And the agents must operate at a series of organizational levels—they must include senior organization leaders who can apply resources and incentives to support implementation, as well as talented, ground level "do-ers." The learning engineer role described above is one example of such a change agent. There must be "agents" at different level—in faculties, in senior university administration positions, within disciplinary fields, and in research agencies prepared to support study and development of best practices. An example of a change agent within higher education would be the group at the University of Colorado–Boulder led by Professor Carl Wieman and colleagues. This group created the PhET interactive simulations for science and math teaching reform and implemented them in classroom settings.[255] This led in turn to systemic Science Education Initiatives at both Boulder and the University of British Columbia, which transformed science education within the universities.[256,257]

While institutional change agents are key, higher education associations can catalyze change more broadly and perhaps more quickly through collaborative efforts that leverage relationships among higher education leadership. For example, the American Association of Universities' Undergraduate STEM Education Initiative, with funding from the National Science Foundation, the Helmsley Trust, and other foundations, has created a networked approach to leveraging change. Participating institutions learn from each other, with AAU providing a hub to support interaction among the change agents and help disseminate their work. The American Physical Society and the American Association of Physics Teachers partnered to form PhysTEC, which has helped implement teaching reforms developed by the Physics Education Research community at colleges and universities across the nation.[258]

Finally, ***role models*** are needed. Legacy transformation must be recognized as a developmental process; it will not occur overnight. Pilots must be tried and assessed; not all will succeed, so they must be built to fail quickly, enabling the change agents to rapidly move to the next steps. Identifying role models is key—respected organizations, such as first rate implementing departments or schools, or outstanding individuals, are needed to model the change for all to envision and learn from. For example, Arizona State University's effort to develop an online suite of first-year courses through the edX platform as an option for its entering students could provide a pilot for new ways of reorganizing "seat time" and tuition models.[259] The University of Wisconsin is breaking the "seat time" model with competency-based degrees; while Udacity, Georgia Tech, and AT&T have partnered to offer an online master's degree in computer science.[260,261] As another example, edX courses are attempting to break up the lecture aspect of online courses into eight-minute segments interspersed with assessment material to better fit learning patterns. edX provides a suite of tools which makes it easy for its partners to implement this structure. Many such "role models" will be required for study, implementation and attention.

Systems linking together innovations, thinking communities, change agents, and role models have succeeded in bringing change to other legacy sectors. Thought leaders in higher education should encourage the development and maturation of these elements in their own community in order to introduce new educational models that take advantage of online education, learning science, and other advances to extend the reach and effectiveness of their institutions.

Notes

1. We appreciate support from the National Science Foundation for a related workshop, the Learning Sciences and Online Learning Symposium, PIs E. Klopfer and V. Kumar, held in Boston, MA on May 21 and 22, 2015. See https://lsol.mit.edu/agenda/. A report on the workshop is available from the Office of Digital Learning, odl@mit.edu.

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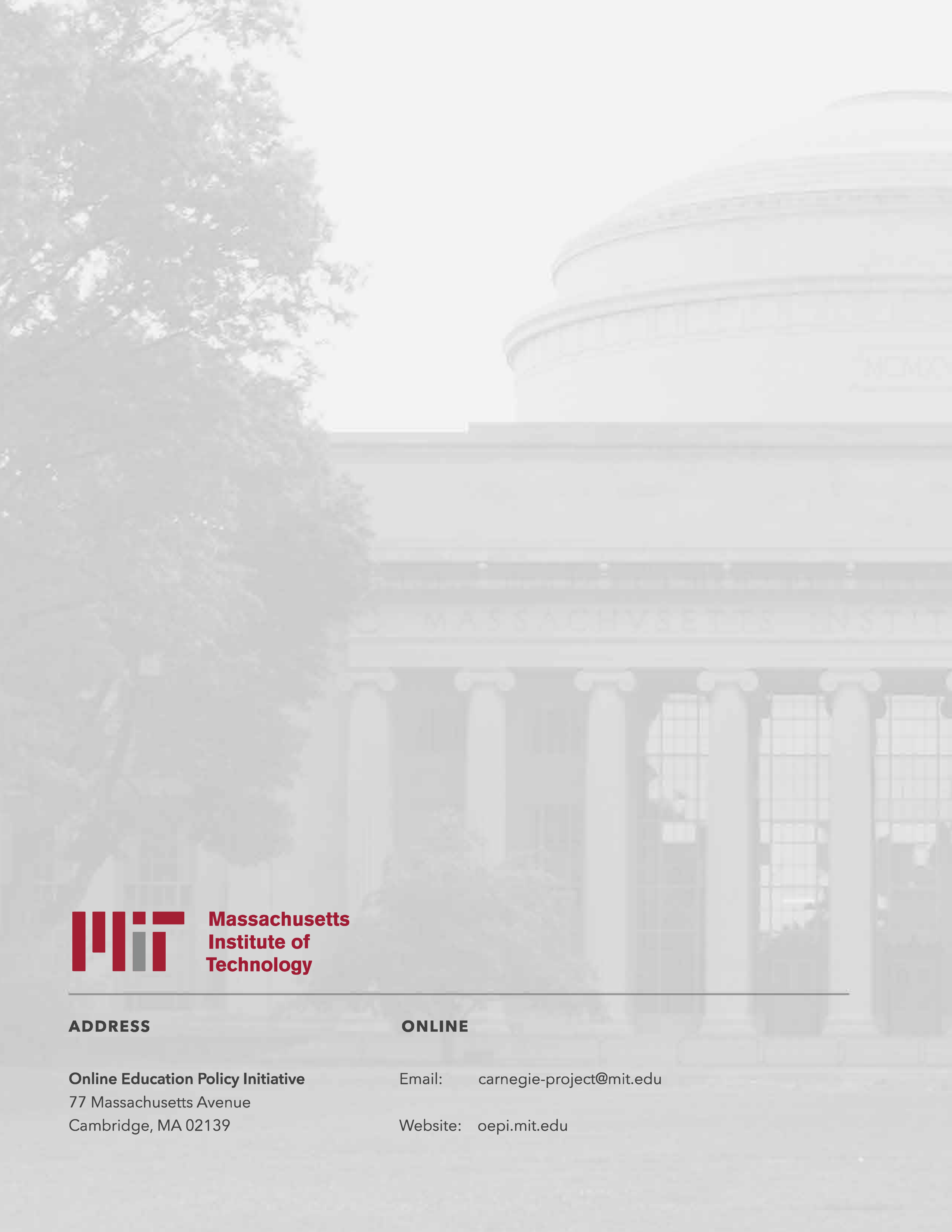

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