Emerging from the heightened attention to higher education access and quality is the potential to substantively improve the learning experience for all students—an opportunity that can be leveraged by technology and actualized through new and creative partnerships. Advances in connectivity and software engineering are offering up sophisticated learning platforms while research on learning is providing new insights into how people learn. Bringing these two often disparate worlds together can inform online learning, and research into online learning can inform learning in all environments.

Achieving this knowledge integration requires collaboration among learning scientists, instructional technologists, faculty members, industry leaders, software engineers, data scientists, data privacy experts, and learners. For coherence, this article draws on natural science and engineering contexts, acknowledging that some aspects of learning are discipline-specific.
A rapidly changing understanding of when and where learning is occurring creates unprecedented opportunity to realize Lee Shulman’s vision of “teaching as community property.” A continuum of face-to-face to online learning environments is emerging, with increasingly creative approaches to laboratory learning in massive open online courses (MOOCs). David Cox, a Harvard neuroscientist, has included do-it-yourself laboratories in his HarvardX course “Fundamentals of Neuroscience.” With a cockroach, a mobile phone, and an open-source bioamplifier called a SpikerBox, students can sit at their kitchen table or in their home office and listen to neuron activity in a cockroach leg. This example flows into another learning environment continuum: from formal to informal learning. Reaching from secondary school students to interested retirees and from academic civic engagement in formal classrooms to citizen science, large data sets are being created and mined by atypical collaborators. An example is Foldit (http://fold.it/portal/), an online game that crowdsources solutions to difficult three-dimensional protein structures, adding human problem-solving and pattern-recognition to computational solutions. Foldit players have solved or refined a number of protein structures, including one that may lead to improved designs for antiretroviral drugs to treat diseases like HIV. Large genomics data sets are also leveraged in online and blended learning environments. Learners are thus no longer constrained by bricks-and-mortar classrooms, and they may be collaborating with other learners halfway around the globe. MOOC participants learn from each other as well as from the instructor, and some form local meet-up groups. Learners in the City University of New York’s Institute for Virtual Enterprise (http://www.ive.cuny.edu/us/) gain international entrepreneurial skills as they participate in a virtual economy that includes 40 global partners and 80 postsecondary institutions in the United States.

Building environments that afford new, high-impact learning opportunities for tomorrow’s citizens and workforce require collaborative expertise. An understanding of the cognitive foundations of learning is necessary, along with intra- and interpersonal skills including motivation and teamwork. This knowledge can then be embedded in emerging contexts and tools for the learning of additional concepts and skills.

Learning from the Science of Learning
Much that is known about how people learn has been synthesized in the books How People Learn and How Learning Works. In brief, learning depends on prior knowledge. Motivation determines what is learned. How learners organize knowledge affects both learning and the application of what is learned. The quality of learning is enhanced by goal-directed practice and specific feedback. The climate of the learning environment—intellectual, social, and emotional—has a significant impact on students’ perception and outcomes. Successful, lifelong learners are able to monitor their learning and adjust their approaches to learning. In terms of research on undergraduate learning in online environments, much
of the focus, especially of meta-analyses, has been on the comparative effectiveness of traditional, completely online courses and blended courses that combine face-to-face and online learning.7

A breadth of disciplines has contributed, and continues to contribute, to the understanding of how people learn. Education research draws on a range of fields and has yet to become fully theory-driven and theory-generating. There is opportunity for a greater coherence and integration of knowledge in the science of learning. Cognitive psychology investigates perception, attention, memory, knowledge representation, mental imagery, language, problem-solving, reasoning, and decision-making, all in controlled laboratory settings. Cognitive science, an interdisciplinary field, brings together artificial intelligence, psychology, philosophy, linguistics, anthropology, and neuroscience and focuses on understanding the mind, often through representation and computation. The learning sciences emerged in the 1990s as an interdisciplinary field looking at "cognition in the wild"—for example, examining what learning looks like in a classroom rather than in a controlled laboratory setting using interventions aimed at specific outcomes. From within disciplinary departments, discipline-based education research (DBER) developed with aims quite similar to those of the learning sciences but deeply situated in the needs and the priorities of the specific discipline, primarily at the undergraduate level. Advances in the neurosciences are also providing insight into learning. There is growing recognition that collaboration among all of these fields, as well as across other relevant social sciences, is imperative to reaching a deeper, richer understanding of human learning.

Even though gaps remain, what has emerged so far from the collective efforts to understand thinking and learning can inform the design of learning environments, including online environments. Cognitive psychology research has provided a solid foundation to guide instruction. A key goal of the undergraduate years is to develop expertise in a major; the student shifts from participating in learning science to becoming a scientist. K. Anders Ericsson and his colleagues have shown that expertise is not transferable from one domain to another and that reasoning and problem-solving in a specific domain is dependent on knowledge and content.8 That's a challenge if a learner is in the third year of study as an economics major and becomes interested in switching to physics. Developing expertise requires deliberate practice with feedback over extended periods of time. If the activity does not sufficiently challenge the learner, or is too difficult, no learning will occur, an important consideration in instructional design.

Expert thinking and reasoning is quite different from novice thinking and reasoning. Curiously, experts have a "blind spot" and cannot remember reasoning as a novice. Numerous studies reveal that knowledge becomes automated and that experts unintentionally omit up to 70 percent of the relevant information when describing a task.9 Experts may be puzzled when a novice is stumped by something they take as obvious—a situation that, unrecognized, can impede teaching and learning. Peer and near-peer mentors can help, as can cognitive task analysis, a research methodology that can unpack experts' knowledge and use it to more effectively structure learning. For example, the technology behind the Carnegie Mellon Genetics Cognitive Tutor (http://www.cs.cmu.edu/~genetics/) was informed by cognitive task analysis of genetics problem-solving. When the tutor was implemented at twelve colleges and universities, statistically significant learning gains in reasoning skills were documented. Cognitive task analysis is time-intensive, however, and the potential to accelerate this work and improve learning environments by analyzing learner data in online environments is tantalizing.10

A number of instructional design principles have been generated from cognitive psychology research findings.11 For example, frequent testing provides practice in retrieving knowledge from memory, which enhances long-term retention. Spaced practice, rather than cramming before a final exam, supports enduring understanding. Elaboration involves extracting key ideas and making one's own mental model; a learner might connect a series of concepts by drawing a concept map to elaborate an understanding of the interconnections. However, catering to the "learning style" of the learner has not been substantiated by research. For instance, although learners learn more from words and graphics than from words alone, extraneous visual detail, such as showing an elaborate photo of a skier on a slope in an inclined plane physics problem, can distract and impede learning. On the other hand, placing relevant text close to the graphic in space or time enhances learning.

The list of instructional design principles continues, and deciding what to use when can be a challenge. Kenneth
Koedinger and his colleagues have proposed a framework that takes into account the type of knowledge to be acquired, the learning that must occur, and the implications for instructional design. For example, as noted earlier, frequent testing may support long-term retention, but it may be less effective in enabling a learner to later transfer understanding. A second example of aligning instructional design with the intended learning goal concerns “flipped” classrooms. Viewing lecture videos online before encountering and solving physics problems in class is an intuitively appealing way to improve instruction. Research by Daniel Schwartz and his colleagues, however, indicates that students are more likely to understand the deep structure of physics and to transfer their learning to new situations if they first encounter a problem followed later by an explanation. On the other hand, being told how to solve the problem before encountering it may have benefits in terms of procedural knowledge. Clearly, instructional design principles informed by learning science can improve technology-enhanced learning environments, but they can also be refined and improved on through research on the learning data generated in those environments.

From the Science of Learning to Undergraduate Learning

Extending the findings of cognitive psychology from controlled laboratory settings to technology-enhanced or bricks-and-mortar learning environments calls out for partnerships. Embodied cognition—the concept that cognition is shaped by the body—emerged from cognitive science and is providing rich territory for partnerships among psychologists, neuroscientists, and DBER scholars. In one example focused on undergraduate physics learners performing angular momentum problems, those who had physically experienced angular momentum by tilting an extended axel of a spinning bicycle wheel outperformed those who had only observed angular momentum. Comparisons of fMRI (functional magnetic resonance imaging) data for the two groups indicate that different regions of the brain are activated while solving the problems. The benefit of physical interactivity can inform how to design hybrid learning environments and how to balance the use of effective simulations with hands-on activities.

With an eye to research to improve undergraduate learning, DBER is catalyzing partnerships. Focusing on science and engineering, a National Research Council report defined the scope of DBER, noting that its long-term goals are to

- help to identify and measure appropriate learning objectives and instructional approaches that advance students toward those objectives;
- contribute to the knowledge base in a way that can guide the translation of DBER findings to classroom practice; and
- identify approaches to make science and engineering education broad and inclusive.

The report synthesized the knowledge of undergraduate learning across the sciences and engineering, finding a solid evidence base for improving students’ conceptual understanding, problem-solving abilities, and use of representations and listing effective instructional strategies that can and ought to be implemented now. Numerous concept inventories have been developed to test conceptual understanding, and some strategies to alter scientifically inaccurate conceptions have been vetted. Conceptual change is particularly challenging for concepts involving either very small or very large spatial or temporal scales. Unlike experts, novices are distracted by superficial details when solving problems and often try to work backward in finding a solution. Open-ended problems and peer-mediated learning help. Representations are often disciplinary shorthand for complex ideas, accessible to the expert but not to a novice. Multiple representations can be effectively used.
to unpack meaning for learners. A range of instructional strategies that actively engage learners can be used to complement or replace the traditional lecture for improved learning outcomes. A recent meta-analysis of research on these strategies revealed that these engaged-learner strategies also increased retention and persistence.16

Gaps in Understanding Undergraduate Learning

To date, much of the research on undergraduate learning has been classroom-based, and only a limited number of studies have disaggregated data to understand similarities and differences among different groups of students. Knowing more about different learners could lead to improvements in college persistence and success, given that fewer than 40 percent of all students who begin college intending to major in a science, technology, engineering, or mathematics field complete a degree in that field. The completion rate is even lower for members of traditionally underrepresented groups in these fields. Further, the four-year degree graduation rate for students with top-scoring SAT or SAT-equivalent scores from the top quartile of socioeconomic status (SES) is 82 percent, contrasted with a graduation rate of 44 percent for students with top-scoring SAT or SAT-equivalent scores from the lowest SES quartile.17 The need for disaggregated data presents both a caution and an opportunity for bringing learning to scale through online environments. That is, a learning intervention that worked with one group of learners may need to be adapted, rather than scaled with fidelity, to a broader group of learners. Online learning environments afford a research opportunity to study implementation across different groups of students. They also offer a chance to identify what works across different groups and different institutions of higher education.

Technology-enhanced learning has the potential to provide insights into how learning occurs over time, over multiple courses, and across disciplines. Longitudinal studies are few, and the development of expertise occurs over longer time periods. As DBER arose within individual disciplines, research on learning and on the application of learning across disciplines has been limited. Understanding and improving the ability of teams to work effectively across disciplines is imperative at a time when meeting global challenges requires the best collaborative innovation of people from diverse cultures with diverse experiences.18

Teamwork is just one of the intrapersonal and interpersonal competencies that are necessary for learning but that have received less attention at the undergraduate level and are difficult to measure.19 Motivation, persistence, metacognition (reflecting on one's own learning), work ethic, communication, and collaboration are examples of other competencies that are critical in determining a learner's actions and success and that have received less research attention at the undergraduate level. As technology-enhanced learning goes global, cultural aspects of motivation and other noncognitive aspects of learning gain increasing importance, and as a result, psychometricians, social psychologists, sociologists, and cultural anthropologists become valued partners in understanding and assessing these competencies.
Opportunities also exist to integrate knowledge across different research communities, including higher education research, institutional research, disciplinary research, information technology research, and research on student support services and advising. Predictive analytics approaches are leveraging student records and intervention data to provide timely support to students to increase retention and success. The Predictive Analytics Reporting (PAR) Framework uses multi-institutional, de-identified data to find patterns to predict student success. PAR has partnered with Starfish Retention Solutions (http://www.starfishsolutions.com/), a platform that optimizes timely access to college services with analytical components that aid institutions in making decisions about investments in various student support services.

Technology can help advance the research on learning, but it is also driving changes in research methodologies. Research and improvement approaches that are continuous and nonlinear are possible in digital environments and may advance our understanding of learning more rapidly than the current “gold standard”: the randomized control trial. A/B testing—in which two alternative approaches are simultaneously used in an online environment—allows for rapid, iterative improvements based on the generated evidence. How cost-effective and efficient A/B testing will be as the research questions and interventions increase in complexity is an open question. But it is clear that the growth of big data is driving the development of the field of data science and learning analytics, again pushing on the need for collaborations and partnerships. In addition, the dramatically shifting terrain
of education research in a digital world calls for new frameworks and expertise in data privacy and protection.22

**Partnerships for Learning in a Digital World**

Integrating the science of learning into technology-enhanced learning environments and developing a research agenda and methodologies to iteratively discover more about learning in these environments depend on the multifaceted partnerships alluded to above. The challenge of widely incorporating evidence-based practices, drawn from research on learning, into teaching practices is far more universal than the challenge of integrating them into technology-enhanced learning environments.23 Evidence of effectiveness alone has not been sufficient to change practice, and a number of efforts are under way to change the culture of teaching and learning in higher education. These efforts include the Association of American Universities’ Undergraduate STEM Education Initiative (https://stemedhub.org/groups/aau) and the National Science Foundation’s Improving Undergraduate STEM Education (IUSE, http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505082) investments. An intriguing example is “An Introduction to Evidence-Based Undergraduate STEM Teaching,” a seven-week professional development MOOC designed to engage and support graduate students, postdoctoral fellows, and faculty in the use of evidence-based practices (https://www.coursera.org/course/stemteaching).

In addition to growing partnerships that will bring together expertise in the science of learning and teaching, information technology, software development, and data privacy, new areas of expertise are emerging and areas of expertise from several fields are converging, creating a new generation of data scientists. Graduate students, envisioning careers as learning engineers, are building robust online learning environments with a research agenda aimed at improved learning, joining instructional designers and academic technologists. Within the sciences, mathematics, and engineering, departments are hiring DBER scholars. These individuals are physicists, chemists, biologists, geoscientists, mathematicians, and engineers with research expertise in how students learn within the discipline. Professional preparation in these emerging fields spans disciplines and will benefit from the growing body of work in the science of team science.

Partnerships to support technology-enhanced education extend beyond the walls of the campus as well. Working collaboratively with industry partners can hone the curriculum to prepare students for the workplace. The National Science Foundation’s Advanced Technological Education program (http://www.atecenters.org/) supports the development of technicians; all projects begin with a robust industry-academic partnership. The National Convergence Technology Center (http://www.connectedtech.org/) prepares information technologists with a curriculum that maintains its currency through quarterly meetings of the Business and Industry Leadership Team. The Nanotechnology Applications and Career Knowledge (NACK) Network (http://nano4me.org/) at Penn State University provides community college students across the country with remote access and control to sophisticated equipment—including field emission scanning electron microscopes and energy (X-ray) dispersive spectroscopy—that they will use in the workplace. The National Center for Welding Education and Training (https://www.weld-ed.org/)
partners with major manufacturers of welding equipment and supplies to be sure that its students have access to the latest welding technology, including competency-based assessment through simulated welding experiences. The Automotive Manufacturing Technical Education Collaborative (http://www.autoworkforce.org/) supports students in 12 states through partnerships with 37 educational partners and 23 automotive industry partners through a range of blended learning models that include working with assembly robots. All of these above examples are offered not only because of the scale of the partnerships but also because they serve as examples of the possibilities of technology-enhanced education. Networked, remote access to sophisticated equipment offers value in many learning contexts, not only in technical education. As with access to large-scale data sets, like genomics data, creating platforms and opportunities for diverse learners in diverse learning environments increases access and opportunity.

As technology advances at warp speed, as research on learning leaps forward in different quarters, and as the demographics of postsecondary learners shift, collaboration will become increasingly important. Reaching across boundaries and developing the ability to fully engage experts in other fields may be the most significant challenge we face in advancing technology-enhanced education.

Notes
23. Singer, Nielsen, and Schweingruber, Discipline-Based Education Research.

This work was developed with support from the National Science Foundation. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation.

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