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Fall 2016

OPEN EDUCATIONAL RESOURCES

MIT OpenCourseWare: How It Began
Shigeru Miyagawa

MIT OpenCourseWare: A Leader in Open Education
Cecilia d’Oliveira and Jeffrey S. Lazarus

edX: Open Education in the 21st Century
Nina B. Huntemann

Engineering the Science of Learning: Developing a Continuous Research Infrastructure for MOOCs to Catalyze Learning Research
Justin Reich

Crosslinks: Improving Course Connectivity Using Online Open Educational Resources
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Editors’ Note

Haynes R. Miller is a professor in the Department of Mathematics; Eric Klopfer is a professor and director of the Scheller Teacher Education Program; and Karen E. Willcox is a professor in the Department of Aeronautics and Astronautics and codirector of the Center for Computational Engineering, all at the Massachusetts Institute of Technology.

Open Educational Resources
Past, Present, and Future

This issue celebrates the past and contemplates the future of open educational resources (OERs). The amount and availability of digital learning material have grown astronomically in recent years. The landscape of entities competing to offer “open” education has similarly grown, and with it the variety of meanings associated with the term “open.”

MIT OpenCourseWare (OCW), launched more than 15 years ago, was one of the first major institutional commitments to open education. The “open” in OpenCourseWare refers to online course materials that are freely available at any time for reuse and incorporation into other programs, for the most part under the Creative Commons license. More recently, massive open online courses (MOOCs) have been offered through both for-profit and nonprofit organizations. But the “open” in MOOC typically means something quite different—open in terms of access for learners, but not in terms of reuse or adaptation of the educational materials themselves.

OER use is part of a more general transformation of the modes of engagement with educational materials, a transformation toward modularization, enabling the materials to be separated and recombined based on the needs of the user, whether student, teacher, or independent learner. The changes are apparent in the modularization of curricula at established institutions, the proliferation of modular learning resources (such as those created by Khan Academy), and the creation of entire institutions built around modular competency-based degree programs (such as the new graduate school of education, the Woodrow Wilson Academy for Teaching and Learning). Associated with these developments, efforts are emerging to maintain and distribute digital resources to ensure that they remain accessible and widely available to diverse communities of teachers and learners.

This issue presents six articles that together survey the history and status of two open education platforms, the opportunities afforded by OERs, and the extent of adoption of OERs—and barriers to their adoption.

The first two articles discuss the history and current state of MIT’s OpenCourseWare. “MIT OpenCourseWare: How It Began,” by Shigeru Miyagawa, recounts the original motivations that led MIT to openly share its teaching materials, and discusses the impact of OCW both at MIT and beyond. In “MIT OpenCourseWare: A Leader in Open Education,” Cecilia d’Oliveira and Jeff Lazarus present a more detailed review of the development of MIT OCW, with descriptions of its enhancements, myriad offshoots, use around the world, and pedagogical impacts.

In the third article, “edX: Open Education in the 21st Century,” Nina Huntemann chronicles the emergence of edX, providing background on the (unexpectedly) long history of open education and organizations dedicated to it. She describes the multiple dimensions of edX, including the technological tools, course portal, and organization, and explains their development and their role in the mission of open online education. These dimensions form the core of what Anant Agarwal...
dubbed a “particle accelerator for learning,” a central entity through which multiple partners can participate, research, learn, and share.

In “Engineering the Science of Learning: Developing a Continuous Research Infrastructure for MOOCs to Catalyze Learning Research,” Justin Reich makes the point that current-generation MOOCs are not constructed to generate insights about what makes these courses succeed or fail for particular learners. Although data have been used to describe course participants and the way they engage with courses, what’s needed are effective theories and practices to make these courses better. Reich suggests a “continuous research infrastructure” to support the development of these theories and practices. This infrastructure necessitates technological, programmatic, pedagogical, and personnel shifts in the MOOC world, and Reich explains how to make those shifts.

The fifth article, “Crosslinks: Improving Course Connectivity Using Online Open Educational Resources,” describes an approach to curating OER materials and making them more accessible to learners. The Crosslinks Web-based application collects links of OER materials organized by topic and shows pre- and postrequisite relationships among topics. Crosslinks is an example of an application that provides a content-tagging framework for OER creators and a contextual search for learners.

Rebecca Griffiths and Nancy Maron, in the final article, “Open Educational Resources: Nearing an Inflection Point for Adoption?,” remind us that one motivation for the development of OERs has been the high cost of textbooks. They evaluate how deeply OERs have penetrated the educational landscape, what the barriers are to adoption of such resources, and what the future may bring. They conclude that progress in reducing the mean costs of educational material has been slower than early advocates had hoped, but adoption of OERs may be reaching an inflection point. Further research on the effectiveness of teaching practices incorporating OERs might help to spur their adoption.

We hope this issue will play a role in the historic movement and progress of OERs, and that it provides material for informed discussion about the future of the dynamic relationship between education and technology.
How OCW was transformed from a leap of faith to a functional enterprise that serves learners all over the world and brings benefits back to MIT.

MIT OpenCourseWare
How It Began

Shigeru Miyagawa

On April 4, 2016, the Massachusetts Institute of Technology celebrated the 15th anniversary of the launch of MIT OpenCourseWare (OCW). On that date in 2001, President Charles Vest announced that the institute would make course material from virtually all undergraduate and graduate courses “accessible to anyone anywhere in the world, through our OpenCourseWare initiative” (Vest 2004). The decision defied the dot-com trend in academia at the time and garnered a front-page story in the New York Times (Goldberg 2001).

Today, MIT OCW offers high-quality educational materials from more than 2,200 MIT courses—virtually the entire MIT graduate and undergraduate curriculum, spanning all five MIT schools and 33 academic units. And nearly 1.5 million people from every corner of the globe visit the OCW site (ocw.mit.edu) each month (figure 1), making it one of the largest online educational sites in the world.

But 15 years ago, OCW was “just an idea—an informed leap of faith that it would be the right thing to do and that it would advance education” (Lerman 2004). OCW had a humble beginning in a small faculty committee formed in the summer of 2000 to develop a proposal for financially sustainable online course dissemination. The idea of giving away the course material was not even remotely part of the group’s charge.

What happened that led the committee, at the very last moment before the report deadline, to advocate for openness, and how this idea took on
a life beyond anyone's wildest imagination, is a study in how an academic institution can tap the talents of its faculty, delve into its values, and exercise academic leadership to forge an innovation that, in tandem with the technological and societal forces of the time, takes on global significance.

The result is that OCW has redefined the relationship between an academic institution and the society it serves, bringing the two closer together with benefits to both.

**Why Openly Share Teaching Materials?**

Shortly after the announcement, a faculty member told me, “The day MIT announced OCW was the proudest day of my career at MIT.” This sentiment was shared across the institute and led to a vast majority (about 75 percent) of tenured and tenure-track faculty contributing their teaching material to OCW (Abelson et al. 2012).

It is not surprising that the idea of openness resonated with the MIT faculty—sharing knowledge is a core value of the institute, as articulated in the MIT mission statement:

> The Institute is committed to generating, disseminating, and preserving knowledge, and to working with others to bring this knowledge to bear on the world’s great challenges.

MIT traditionally fulfilled this mission largely through basic research. Now OCW also substantially supports the mission.

The committee that proposed OCW explored a number of possibilities. Having failed to come up with financially viable and exciting elearning options for MIT to pursue, the members reached deep into the school’s core values and hit on the idea of opening up the institute’s teaching materials.

When I chaired the MIT OpenCourseWare Faculty Advisory Committee (FAC; 2010–2013), I was often asked why MIT decided to give away its teaching material. I came back to something that Charles Vest said:

> When you share money, it disappears; but when you share knowledge, it increases.

This captures the essence of OpenCourseWare and celebrates the principle of openness that is at the core of MIT’s mission.

**A Case Study in Decision Making**

**Faculty Group Origins**

The MIT Council on Educational Technology (MITCET) was created in 1999, largely through the initiative of Provost Robert Brown, “to provide strategic guidance and oversight of MIT efforts to develop an infrastructure and initiatives for the application of technology to education.” It was cochaired by Brown and Hal Abelson, professor of computer science and engineering.

MITCET selected McKinsey and Company to assist in identifying potential online educational projects for MIT and to conduct interviews on campus to gauge the community’s reaction to them. The work took three months.

Meanwhile, new online educational enterprises were being announced: UNext (a collaboration of Stanford,

Reflecting the excitement of the time, the MITCET-McKinsey report (unpublished) recommended that MIT undertake a study to launch “Knowledge Updates,” minicourses based on MIT’s strength in cutting-edge science and technology. In April 2000 Provost Brown created the Life-Long Learning Study Group, led by Associate Dean of Engineering Dick Yue, with the charge of formulating a plan for Knowledge Updates, with up to $2 million in startup investment to launch an enterprise that should be financially self-sustaining within two years (Abelson 2008).

Evolution of an Idea

The group pursued the Knowledge Updates project with the genuine hope of creating a successful enterprise. But there were questions: Would the venture divert resources from MIT’s core mission? Would it dilute MIT’s brand? Would it be financially sustainable? These and other questions came to a head in the group’s final meeting in October 2000 (Lerman and Miyagawa 2002).

Early Challenges

Extensive analysis indicated that the Knowledge Updates proposal seemed doable, but the enterprise struck the group as lacking in the kind of excitement one would expect of an MIT initiative. Moreover, the group’s financial projection from the most realistic of several business models showed the enterprise reaching a break-even point a few years into the operation, and after that essentially remaining in that state. It lacked the “hockey stick” spectacular growth of a successful venture.

Also, the basic nature of the product to be offered was in question: while the committee assumed that the updates would be hours or even weeks and months long, alumni survey responses indicated that some preferred 30-minute “mini” updates, a format that the committee did not feel entirely comfortable with.

Despite these uncertainties, the committee included in its final report an extensive discussion of Knowledge Updates accompanied by analysis and numerous attachments.

A Shift in Thinking

Midway into the October meeting, the committee’s interest shifted to offering the teaching material for free. Yue laid out the plausible business models, reviewed pros and cons, and concluded that a business venture was possible, although the prospect was less than exciting. Then, reminding the group of an idea that had been informally mentioned earlier without much conviction, he suggested an alternative proposal to consider: to simply give away the teaching material instead of charging for it. Some committee members asked, “Is it OK to do that, and would anyone care if MIT did?”

At the same time, we were aware that MIT faculty members had already put up their own teaching materials on the Web. When asked why they did so, they said, without exception, that they were experimenting to see whether putting teaching material on the Web could improve their courses. They weren’t getting any compensation, and they were sacrificing their research time to do it. We felt it would be highly questionable for MIT to take the teaching materials produced by these faculty members who are committed to teaching excellence and turn them into a for-profit business. The idea of giving them away to anyone, anywhere, was appealing because it would give global expression to MIT faculty members’ commitment to excellence in teaching.

Giving away teaching materials to anyone, anywhere, gives global expression to MIT faculty members’ commitment to excellence in teaching.

OCW Is Born

Once the committee members overcame the shift from thinking about creating a for-profit business enterprise to the idea of making materials and information freely available, they quickly embraced the idea as the right thing for MIT to do and came up with the term OpenCourseWare, drawing both the name and inspiration from an earlier MIT effort, open source software.
In October 2000 the Life-Long Learning Study Group presented its report to the MIT Academic Council. The report contained a treasure trove of data gleaned from interviews with 50 external organizations engaged in elearning (to understand the online education landscape), responses to an extensive survey sent to 2,500 alumni (deemed potential clients for Knowledge Updates), interviews with 60 MIT faculty members who had already put their teaching materials on the Web, and a series of elaborate business models, all done in collaboration with a team from the consulting firm Booz Allen Hamilton.

The report included—"almost as an afterthought" (Abelson 2008)—the following suggestion, fundamentally defying MITCET’s original charge to the group:

A revolutionary notion of OpenCourseware@MIT could radically alter the entire lifelong learning and distance learning field and MIT’s role in it and should be seriously considered.

Guiding Principles and Institutional Leadership
The committee agreed on a principle that became a cornerstone of OCW: all materials offered should be cleared of copyright so that users can freely use them to learn and to teach. When Harvard law professor Larry Lessig and his colleagues launched the Creative Commons in 2001 to furnish licenses for appropriate use of copyrighted material free of charge, MIT OCW adopted this mechanism for virtually all its materials.

The principle of faculty governance was central to the planning phase of OCW. Chancellor Larry Bacow told the OCW planning group that MIT could not announce the initiative without extensive discussion within the community. The group met with representatives of 33 departments and major administrative units. Although most voiced support, some raised concerns, such as the risk that OCW could devalue MIT’s reputation by putting up low-quality material (Abelson 2008). The culmination of these discussions was a presentation at the February 2001 faculty meeting, at the end of which President Vest spoke with conviction about OCW. The Record of the Faculty Meeting states that, noting the trend toward commercialism in higher education,

MIT could be a disruptive force by demonstrating the importance of giving information away. Vest noted that in the 1960s and ’70s MIT had a big impact on education, not only from textbooks that were published by the faculty but also from the course notes, problem sets, and other materials our graduates took to other institutions where they used them in their teaching. OCW, he stated, gives us another chance to make such an impact.

Thus, while faculty governance was at the heart of decision making that moved the initiative forward, academic leadership played an equally important role, and MIT was blessed with strong and open-minded leaders. The role of President Vest was obviously critical. Others who played a key role in guiding OCW went on to leadership positions at major universities. Provost Brown, who shepherded the discussion from the outset, became president of Boston University in 2005. Rafael Reif, who took over as provost after Brown and continued to nurture OCW, became the 17th president of MIT in 2012. Chancellor Bacow, who called for the extensive discussions to get as many on board as possible, became president of Tufts University in 2001.

Off and Running: Funding, Staffing, and Sustainability
Funding
Of course, giving away the course material for free does not mean that there is no cost to set it up and operate. Fortunately, Vest’s overture to William Bowen, president of the Mellon Foundation, was met with enthusiasm. Bowen in turn contacted Paul Brest, president of the Hewlett Foundation, and the two foundations agreed to fund OCW. Ira Fuchs, the Mellon Foundation

3 The Academic Council consists of the institute’s senior leadership and the chair of the faculty.


program officer for the grant, said that the foundation “really bought into the ambitious and unique nature” of OCW (Walsh 2011, p. 62). Without this generous funding, OCW would not have seen the light of day.

**Staffing and Implementation**

Once the grant proposal to Mellon and Hewlett (coauthored by Brown, Abelson, and Faculty Chair Steve Lerman) was approved and an initial $11.5 million awarded, Anne Margulies, former CIO of Harvard, was hired in May 2002 as OCW executive director. Her first task was to create a 50-course pilot by September of that year (Walsh 2011). She recalls, “All eyes were on us. There were lots of skeptics, but the overwhelming majority were excited.”

Margulies participated in the 2002 UNESCO Forum on the Impact of Open Courseware for Higher Education in Developing Countries, held in Paris. Many university presidents and rectors from developing countries were in attendance, and their message was “Thank you, MIT.”

It was at the Paris forum that the term open educational resources (OERs) was coined for “free tools and content...that can include full courses, textbooks, streaming videos, exams, software, and any other materials or techniques supporting learning” (Walsh 2011, p. 43; also see Griffiths and Maron in this issue). The Hewlett Foundation set up an OER division and appointed Catherine Casserly to head it; she went on to play a major role in OERs around the world.

In addition to creating a 50-course pilot in her first four months, Margulies had to complete the posting of 500 courses by October of 2003. This deadline, imposed by the funders, had to be met before delivery of the balance of funding. To the credit of Margulies and her team, which at the peak numbered 50 full-time employees and outside consultants (Walsh 2011), the deadline was met and Hewlett and Mellon awarded the remaining $16 million, which made it possible to complete the OCW posting of 1,800 courses by 2007.

Margulies left in 2007 to become assistant secretary for information technology and CIO for the Commonwealth of Massachusetts. Cecilia d’Oliveira, who had been the director of technology for OCW, took over and has ably shepherded OCW ever since (see d’Oliveira and Lazarus in this issue).

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**Sustainability**

There remain questions about how to sustain OCW financially. MIT currently covers about half the cost of the $4 million annual budget. Besides the original funding from Hewlett and Mellon, OCW has received generous support from the Ab Initio Corporation, the Stanton Foundation, MathWorks, Accenture, Telmex, and others. It also receives approximately $350,000 annually in small donations from thousands of users around the world (Abelson et al. 2012). As grant reserves deplete, MIT and OCW must find ways to sustain the initiative.

Beyond the financial challenge, OCW now shares the stage with MOOCs (massive open online courses). To seek opportunities and address the challenges, the OCW executive director works closely with the OCW advisory committee, composed of faculty members, students, and administrators.

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**The message from many university presidents and rectors from developing countries was “Thank you, MIT.”**

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**Impacts at MIT**

OCW has significant and beneficial impacts on campus at MIT. Students use OCW resources such as problem sets and exams for study and practice. Freshmen report that they checked out the school by looking at OCW before deciding to apply. Because faculty have easy access to the course material that their students use in other courses, OCW serves as a broad communication channel among faculty. And alumni access OCW materials to pursue lifelong learning.

It was hoped that OCW would benefit teaching on campus, and there is anecdotal evidence that it does. Before a course goes up on OCW, the materials are placed on the staging server, where the posting faculty member can view all other courses. Margulies has observed that a number of faculty members have looked at these other courses and seen features they wanted to

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6 Author interview with Margulies on March 7, 2016.

7 This was the original target, and was celebrated at the time (https://www.youtube.com/watch?v=tbQ-FeoEvTI).

8 Differences between OCW and MOOCs are outlined in Abelson et al. (2012).
incorporate into their own course. And Steve Carson, who served as the OCW communications officer for many years, noticed a lag from the time faculty members agree to contribute material to when they actually submit it. He guessed that as faculty realized their material would be viewed by the world, not just their students, they spent more time developing and polishing their course content.

MIT has also benefitted from the attention it has received. Hundreds of media outlets from around the world have featured OCW. For example, Wired (Diamond 2003) reported that, before OCW,

no institution of higher learning had ever proposed anything as revolutionary, or as daunting…. MIT earned the distinction as the only university forward-thinking enough to open-source itself.

There are more than 1,000 independently translated versions of MIT OCW courses available in 10 languages other than English.

International Impacts

International Users of MIT OCW

There are now over 2,200 courses on OCW. There are also more than 1,000 independently translated versions of MIT OCW courses available in 10 languages other than English: Arabic, Chinese (simple and classical), Farsi, French, Japanese, Korean, Portuguese, Spanish, Thai, and Turkish. For users in developing regions of the world such as sub-Saharan Africa where Internet access is cost prohibitive, unreliable, or nonexistent, OCW helps to bridge the “digital divide” through its mirror site program on external drives, and there are more than 350 of these sites.

Over 200 million people from virtually every country in the world have accessed these resources. Many (42 percent) are students at other institutions, both college and precollege, and others are “self-learners” looking to enrich their professional and personal lives (43 percent).

As an example of self-learners, Jean-Ronel Noel and Alex Georges from Haiti wanted to develop solar panels for their country but needed guidance in electrical engineering. They found it through OCW. Noel told the OCW staff,

I was able to use OCW to learn the principles of integrated circuits. It was much better than any other information I found on the Internet.

Their company, Enersa, has made solar-powered LED lighting available in almost 60 Haitian towns and remote villages (d’Oliveira et al. 2010).

Teachers account for 9 percent of those who access OCW, and have described a variety of ways in which they incorporate OCW material into their classes (d’Oliveira et al. 2010). For example, Triatno Yudo Harjoko, head of the Architecture Department at the University of Indonesia, said that to redesign the curriculum he and his colleagues turned to MIT OCW as an immense comparative database (d’Oliveira et al. 2010):

We try to understand how the courses are formulated and what the expected outcomes are. This gives us an important perspective on the learning process.

OCW at International Universities

To give some examples of successful OCW sites from around the world, Delft University of Technology in the Netherlands offers undergraduate and graduate courses in energy, environment, health, water, and infrastructure and mobility, under a Creative Commons International License.

From the beginning much of the interest in OCW was in non-English-speaking countries (Walsh 2011). For example, in 2005 six of the top universities in Japan formed the Japan OCW Consortium, and many have been among the most active OCW members outside of MIT and contributed innovations to the community.

The University of Tokyo OCW started in 2005 and now has 1,406 courses posted. Led by Takeo Fujiiwara, a professor of engineering, a unique feature of the UTokyo OCW is that the courses are virtually all video-based with a complete transcription of each video lecture made available, and a search engine has been developed to enable searches of both text and video. Similar to MIT, UTokyo OCW clears copyright consistent with Creative Commons.

Kyoto University OCW also started in 2005, and as of 2015 had 660 OCW courses, most of them with video lectures. The courses are taught in Japanese, English, or, in a few cases, French. Led by Naoko Tosa, a professor of media art, KU OCW posted videos on YouTube before MIT OCW hit on that solution.
Adaptations of OCW

In 2004 the MIT OCW leadership began to speak with other institutions about adopting OCW. At the University of California, Irvine, the OCW site, led by Larry Cooperman and Gary Matkin, hosts the California Subject Examination for Teachers—Preparation Resources, open chemistry, public health, and technology transfer and entrepreneurship as well as TED/TEDx talks given by UCI faculty members and researchers.

The OCW Consortium was formed in February 2005 with the goal of extending the reach and impact of OCW by encouraging its adoption around the world (Walsh 2011). The consortium changed its name in 2014 to the Open Education Consortium (www.oeconsortium.org) and now boasts 266 members from 48 countries. Moreover, the movement has expanded beyond universities to community colleges, free online textbooks (see, e.g., OpenStax, https://www.openstaxcollege.org/books), and free and open medical resources (e.g., Boston Children’s Hospital Open Pediatrics, http://openpediatrics.org).

Concluding Remarks

OCW was transformed from an informed leap of faith to a functional enterprise that serves learners all over the world and returns benefits to MIT. It is a “bold creation” (Bowen, foreword to Walsh 2011) that changed the equation for elearning from the obsession with commercialism of the dot-com era to a demonstration of the enormous value in freely sharing knowledge produced by an academic institution. The 1.5 million people who access OCW every month illustrate the demand for high-quality teaching materials among students, self-learners, and educators.

Time will tell if OCW will be sustained largely in its present form, or if new technologies and societal forces will drive its mission beyond the vision of the committee that proposed it back in 2000.

Acknowledgment

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OCW uses the Internet to inspire learners and enhance teaching, both at MIT and around the world.

MIT OpenCourseWare
A Leader in Open Education

Cecilia d’Oliveira and Jeffrey S. Lazarus

MIT OpenCourseWare (OCW; ocw.mit.edu) is a free, publicly accessible Web-based resource that offers high-quality educational materials from more than 2,300 courses at the Massachusetts Institute of Technology—virtually the entire graduate and undergraduate curriculum, reflecting the teaching in all five MIT schools and 33 academic units. This broad coverage in all disciplines makes OCW unique among open education offerings. MIT continually updates OCW, adding new courses as they become available and refreshing existing courses with new materials. More than 1,000 MIT OCW courses have been independently translated into at least 10 languages.

Through OCW,¹ MIT faculty share their teaching materials with teachers and learners around the world. Educators use these resources for teaching and curriculum development, while students and others draw on them for self-study or supplementary use.

By longstanding MIT policy, in most cases faculty members own the intellectual property rights in course materials they author (this is not universally true in academia). OCW course materials are offered under a Creative Commons license and may be freely used, copied, distributed, translated, and modified by

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Cecilia d’Oliveira is associate dean of digital learning at MIT. Jeff Lazarus is a contributing writer.

¹ OCW refers to both the online offerings and the staffed program.
anyone anywhere in the world for noncommercial educational purposes. OCW attracts about 2.5 million visits in a typical month, and to date more than 200 million people from virtually every country have accessed these resources. OCW is also used widely on campus at MIT.

From the start, the OCW mission has been twofold:

1. Publish the materials used in MIT courses based on free and open principles, and
2. inspire others to do the same.

The MIT faculty who first proposed OCW embraced the concept of free and open access to educational materials because they believed that open sharing would encourage other educators to use the resources to enrich their own teaching, and that free and open access would reduce financial, geographic, and political barriers to education for a worldwide audience of learners eager for knowledge. This article traces the evolution of OCW and how it has helped to validate the faculty's premise.

OpenCourseWare and the MIT Faculty

MIT faculty are the engine that powers OCW, voluntarily contributing almost all the course materials, which they have created. What motivates them to do this? First, OCW was the brainchild of MIT faculty, not an administrative undertaking (see Miyagawa in this issue). Nevertheless, there was widespread skepticism and debate among the faculty.

OCW needed a good cross section of faculty to sign on in order to pilot the concept, help work out kinks in the publication process, and demonstrate that it would produce a good result that would, everyone hoped, be well received by the public. Sympathetic faculty were recruited and participation was initially incentivized with a modest financial stipend using grant funds earmarked for that purpose (the stipend was reduced over time and eliminated in 2007).

OCW did indeed catch on, and website traffic, user survey response, unsolicited email feedback, media reviews, and awards2 exceeded all expectations. Success breeds success, and more faculty agreed to publish their materials. By the time OCW reached 1,800 courses in 2007, well over 70 percent of faculty had participated. Since then the number of active faculty represented on OCW has varied from 60 percent to 70 percent, reflecting faculty turnover and availability of sufficient OCW resources to meet publishing demand.

OCW materials may be freely used, copied, distributed, translated, and modified by anyone anywhere for noncommercial educational purposes.

Some faculty draw a comparison between publishing their course materials on OCW and publishing their research results. OCW provides a platform for showcasing the instructional dimension of faculty work, recognition of which historically has been subordinated to research. Moreover, as MIT Professor Paul Penfield put it back at the start of OCW, “Everybody knows that the way to make progress in science is by using the best results of others—’standing on the shoulders of giants’ is one way of expressing this idea. That’s why we publish scientific results. OCW will let the same thing happen in education.”3

Faculty benefit in other ways as well. For example, through OCW they see what and how their colleagues are teaching in other courses and disciplines. For some OCW is a helpful tool for advising students. And a 2005 faculty survey found that about a third of faculty believed that their participation in OCW helped them improve their on-campus courses.

While each contributor may have a somewhat different perspective on the value of OCW and reasons for participating, their views mostly come down to this: They love teaching and, in line with MIT’s core mission, they believe their purpose is to create and impart knowledge not only to MIT students but to society at large.


<table>
<thead>
<tr>
<th>Year</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>• OCW announced in The New York Times</td>
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</tbody>
</table>
| 2002 | • **32 courses published**  
• Pilot version goes live with 32 courses on a small server at MIT  
• Spanish and Portuguese translations added |
| 2003 | • **500 courses published**  
• Official launch in October  
• First OCW content management system (CMS) and publishing infrastructure implemented to support large-scale publication and worldwide content distribution  
• Chinese translations added |
| 2004 | • **900 courses published**  
• OCW adopts Creative Commons license (http/terms/#cc)  
• Other institutions work with MIT to create their own OCW  
• First mirror site established in Africa |
| 2005 | • **1,250 courses published**  
• OCW begins updating previously published courses  
• OpenCourseWare Consortium formed (since renamed the Open Education Consortium; www.oeconsortium.org) |
| 2006 | • **1,550 courses published**  
• OCW Consortium meets in Kyoto, portal launched  
• OCW Secondary Education concept developed  
• Thai translations added  
• OCW begins archiving retired courses to MIT DSpace digital archive (https://dspace.mit.edu) |
| 2007 | • **1,800 courses published**  
• New monthly traffic record: over 1 million visits  
• Publication of virtually all MIT courses completed  
• Highlights for High School (http/high-school) launched |
| 2008 | • Audio/video content added regularly to YouTube, iTunes U, and Internet Archive  
• Farsi translations added  
• OCW ramps up online fundraising using expanding email newsletter list |
| 2009 | • **1,950 courses published**  
• 50 million visits since inception  
• New monthly traffic record: over 1.5 million visits  
• 1 million visits to Highlights for High School since launch  
• 1 million visits from the MIT community since inception  
• 225 mirror sites around the world |
| 2010 | • **2,000 courses published**  
• Course Champions fundraising program launched  
• Supplemental Resources (http/resources) section provides 30 complete educational materials  
• New CMS and publishing infrastructure implemented  
• “Code of Best Practices in Fair Use for OpenCourseWare” completed and adopted  
• OpenStudy pilot explores “social learning” |
<table>
<thead>
<tr>
<th>Year</th>
<th>Milestones</th>
</tr>
</thead>
</table>
| 2011 | - Initial OCW Scholar courses (/courses/ocw-scholar), designed for independent learners, are launched  
- OCW celebrates “A Decade of Open Sharing”  
- OCW launches corporate underwriting/sponsor program  
- MIT launches MITx (https://www.edx.org/school/mitx) initiative to offer fully online MIT courses through an online interactive learning platform |
| 2012 | - 2,150 courses published  
- 100 million visits since inception  
- OCW website redesigned to improve and update user experience  
- Turkish course translations and Korean video translations added  
- New Office of Digital Learning (odl.mit.edu) becomes umbrella organization for OCW, MITx, and other digital learning programs at MIT |
| 2013 | - New monthly traffic record: over 2.9 million visits  
- OCW Educator (/educator) launched, providing insight on how courses are taught at MIT  
- Highlights for High School website redesigned for better user experience |
| 2014 | - 2,250 courses published; 800 older courses archived  
- 150 million visits since inception  
- OCW exceeds 1 billion page views since inception  
- Courses with full video lectures reach 100 |
| 2015 | - 2,300 courses published  
- Interactive transcripts allow search within video materials  
- 100 courses in OCW Educator have Instructor Insights pages  
- MIT Crosslinks (/courses/crosslinks) integrated with OCW |

**OCW: A Record of Innovation**

Today, OpenCourseWare is a cornerstone of MIT’s commitment to open sharing of educational resources. OCW continues to grow, with more new and updated courses, more video and interactive resources, and enhancements like OCW Scholar and OCW Educator. Table 1 summarizes milestones over the past 15 years.

**Content and Features**

**Core Publication**

The core of OCW is publication of the materials that faculty use in their on-campus courses. Typical content may include:

- **Planning materials**—syllabus, calendar, pedagogical statement, and faculty introduction of the course
- **Subject matter content**—lecture notes, reading lists, full-text readings, video/audio lectures
- **Learning activities**—problem sets and solutions, essay assignments, quizzes, exams, labs, and projects

Some OCW courses have multiple versions, reflecting their evolution over time. Not surprisingly, course content in some disciplines (e.g., the life sciences) is more susceptible to change than that of others (e.g., history). OCW updates courses based on faculty requests, obsolescence of content, and available staff resources.

Figure 1 depicts the broad array of MIT’s undergraduate OCW course offerings and the fact that a large part of the undergraduate curriculum is represented on OCW (the extensive coverage of graduate courses is not shown).

**Highlights for High School (HFHS)**

OCW features a variety of material that leverages existing courseware to serve audiences with special interests. HFHS (/high-school⁴) was the first such special feature, added in 2007. It presents OCW materials that are most useful for high school students and teachers. Its primary goal is to inspire high school students to pursue studies in science, technology, engineering, and math (STEM) subjects, though it also has many resources in the humanities and social studies.

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⁴ Here and throughout, unless otherwise indicated, OCW web addresses preceded by a slash begin with http://ocw.mit.edu.
Students use HFHS materials to supplement their course work, to study subjects not offered in their schools, and to prepare for exams (including Advanced Placement tests). Teachers and parents of homeschoolers use these resources for course preparation, assignments, independent study projects, and other innovative teaching purposes.

The HFHS website is organized into two main sections: Subjects and Exam Preparation. The subjects are those that high school students are likely to encounter, such as mathematics, physics, and biology. The Exam Preparation section, aimed at students who are getting ready to take AP exams in biology, calculus, chemistry, or physics, offers materials to supplement the students’ classroom learning. Relevant OCW course materials are easily searchable by topic.

The ChemLab Boot Camp (/high-school/chemistry/chemistry-lab-boot-camp) is an innovative video series.
in a reality TV format that follows a group of freshmen through a 4-week course that introduces them to an MIT chemistry lab environment (the series was part of the 2012 MIT-Dow Chemistry Outreach Project). Additional HFHS materials are developed by MIT students in the MIT Educational Studies Program (ESP).[^5] HFHS averages about 45,000 visits per month.

**OCW Scholar**

In 2010, OCW received a 3-year grant of $2 million from the Stanton Foundation to publish materials for foundational courses structured for independent study. These OCW Scholar (/courses/ocw-scholar) courses are relatively complete first-year college-level core courses designed for independent learners who may have limited access to resources such as textbooks, libraries, or subject-matter experts. Scholar courses feature

- units organized into learning modules that take the learner through a logical progression of course topics;
- complete lecture videos by world-class MIT faculty;
- richer content than “regular” OCW courses, including (depending on the course) detailed notes and slides integrated from multiple MIT on-campus courses as well as new content specifically developed for the Scholar course;
- applets, simulations, and multimedia visualizations to illustrate concepts;
- learning aids such as video “recitations” showing step-by-step problem-solving techniques as well as homework problems and exams with explanations and solutions; and
- links to selected websites with related materials for further study.

There are 12 Scholar courses currently available, with another in the pipeline.

**OCW Educator**

OCW Educator (/educator) was conceived by the OCW Faculty Advisory Committee, and its two principal goals are to

- articulate and share the educational ideas, practices, and pedagogical expertise of MIT faculty; and
- enhance users’ (especially educators’) ability to make the best use of OCW materials by helping them understand the context and manner in which the materials are used on campus.

The primary component of OCW Educator is This Course at MIT (/courses/this-course-at-mit), which provides background about how the course has been taught at MIT, including course outcomes, prerequisites, other curriculum information, the kinds of students taking the class, assessments, and student time investment.

This section often includes Instructor Insights about how they structured and taught the course. The Insights section may also include video interviews with the instructor and video of classroom activities.

OCW Educator also provides a structure and format for publishing project-based or experiential courses, which do not align well with standard OCW content as they have no syllabus or lecture notes, for example. One such course is 18.821 Project Laboratory in Mathematics (/courses/mathematics/18-821-project-laboratory-in-mathematics-spring-2013), in which students do mathematics research. The site has extensive observations about how the course works and why it affords an extraordinary learning experience.

A related resource on OCW is the MIT Curriculum Guide (/courses/mit-curriculum-guide), designed to help educators and other users understand how MIT sequences its courses in each discipline and what courses are required for a complete program of study.

OCW Educator supports a new role for OCW as education at MIT is transformed through the use of digital technologies and new research-based teaching practices: using the Internet to inspire and enhance innovative classroom teaching, both at MIT and around the world, by disseminating what faculty at MIT are doing and learning.

**Supplemental Resources**

More than 50 Supplemental Resources (/resources)—videos, textbooks, teaching guides, manuals on lab techniques, and background materials—help educators and learners get the most out of OCW. They do not necessarily correspond to a specific OCW course, but may instead be relevant to many different courses.

**Translations**

Other organizations and institutions translate OCW content for their audiences and deliver the translated versions on their own websites. Languages include

[^5]: ESP has been helping high school students since 1957, focusing on subjects that reflect MIT’s strengths in STEM topics. See http://esp.mit.edu.
Spanish, Portuguese, Chinese (simple and classical), Thai, Turkish, Farsi, Arabic, Japanese, French, and Korean. We are aware of more than 1,000 translations of MIT OCW courses. This number includes multiple translations of certain popular courses.

Some institutions are formal “translation affiliates”—they share the goals of OCW and have agreed to uphold certain quality assurance and open licensing standards. MIT OCW links to affiliate-translated courses from their corresponding OCW courses and from the OCW course finder page (/courses/translated-courses).

**Search Features**

A variety of tools help users navigate OCW’s vast collection of courses and other educational assets. The OCW search engine (powered by the Google Search Appliance) can be set to retrieve either whole courses or specific resources based on the user’s search criteria. A customized course finder feature can identify OCW courses by topic, MIT department, or MIT course number.

**OCW pulls together relevant materials from courses related to energy, entrepreneurship, the environment, introductory programming, life sciences, and transportation.**

The OCW homepage presents convenient lists based on popular search categories such as courses with audio/video lectures, online textbooks, most visited courses, newly published courses, OCW Educator pages, OCW Scholar courses, and Supplemental Resources. From the OCW Educator page, users can perform course searches based on instructional approach or different types of teaching materials (e.g., lecture notes, problem sets). Users can also find links to all courses from translation affiliates.

Some subjects appear in many courses scattered throughout MIT’s complex academic structure. OCW pulls together relevant materials from all MIT schools and departments, spanning courses related to energy, entrepreneurship, the environment, introductory programming, life sciences, and transportation. For example, energy, an area in which the institute has been a research leader throughout its history, includes some 50 courses in physics, engineering, environment, economics, and management, among others.

Another feature, not part of OCW per se but accessible via OCW, is Crosslinks (/courses/crosslinks; see Miller et al. in this issue), a study site maintained by MIT students that connects topics across courses. Every topic page has links to materials that MIT students have found helpful, organized into five sections:

- **learn**—links to courses and other resources that explain the topic
- **prepare**—prerequisite topics useful for understanding the concept
- **relate**—related topics
- **advance**—topics that “come after” or build on the topic
- **apply**—real-life, interesting applications of the topic.

Many Crosslinks topics point to materials in OCW courses, which in turn have links to relevant topics on the Crosslinks site.

Ensuring that users have the tools to find what they need on the OCW website is an ongoing challenge and improving this experience is a high priority for site curators.

**Outreach**

OCW uses a blog, a monthly online newsletter, Facebook, and Twitter to keep subscribers and followers informed of new courses, new features, and other developments. Currently there are about 85,000 blog readers, 250,000 newsletter subscribers, 300,000 Facebook followers, and 150,000 Twitter followers. Because OCW use is completely anonymous (it requires no registration or signup), direct communication is possible only with users who have either signed up for one or more of the online outreach services or initiated contact through email or the Contact Us form on the website. To date, OCW has received and processed over 180,000 inquiries from users.

Notices on the website direct users’ attention to OCW news or items of interest. The subscriber lists and
website “ads” are used to encourage people to donate to OCW during periodic online fundraising campaigns. There is no commercial advertising on OCW.

**Production and Distribution**

**Publication**

Although it has grown enormously in size, richness, and features, OCW is essentially a simple website with mostly static content. Its implementation in spring 2002 was a “proof of concept,” quietly initiated with 32 courses, all hand-coded HTML web pages on a server at MIT. But with the high-profile fall 2003 launch of 500 courses, which required more staff working with more faculty, OCW had to develop a systematic, scalable production method, workflow, and supporting technical infrastructure. And so began the development of a more sustainable publication process (while simultaneously continuing to develop course content web pages).

The process has six steps (figure 2). The three primary goals of the publication process are to (1) promote a steady pipeline of new and updated materials to keep OCW vibrant and current, (2) ensure a very high quality, polished publication that meets the high standards of MIT faculty, and (3) minimize the burden on faculty who volunteer to contribute their materials.

In the early days OCW tracked all activities associated with producing a course via an elaborate system of Post-It notes on whiteboards. In 2003 work began on development of a customized content management system (CMS) based on a Microsoft CMS product available at the time. Initially, the design goals for the CMS were to manage content at the course and resource level, manage the website “global pages,” provide a platform that would support team collaboration, and interoperate with OCW’s worldwide content distribution system provided by Akamai (see below). OCW also built a companion FileMaker (FM) workflow management and tracking system to capture detailed course status and workflow information not included in the CMS.

Enhancements were regularly made to the CMS and FM platforms to support the OCW publication process, including through faculty recruitment, DSpace archiving, website analytics reporting, and user feedback management.

In 2010, working with MIT Information Services and Technology and the MIT Libraries, OCW completed a landmark project to replace its CMS. The new system, still in operation, is based on the open-source Plone software and enabled significant improvements in OCW website usability and features. But the infrastructure is now reaching a point when it too will need to be replaced.

With these and other tools developed over the years OCW’s operational efficiency and effectiveness greatly improved. For example, a deliberative site curation process affords greater use of the breadth and depth of OCW publication, improving its value and usability. Site curation involves activities such as analysis and improvement of a course portfolio’s currency and relevance to the MIT curriculum in order to identify materials in need of update as well as gaps between courses published on OCW and the actual curriculum taught at MIT.

To minimize the faculty time commitment for participating in OCW, most of the actual work of preparing a course for publication is managed by OCW staff in collaboration with Sapient Corporation, an outside service provider that handles much of the content data entry and website authoring. Faculty make their materials available, identify third-party “objects” in their materials that have been created by others, consult on the preparation and display of their materials, and approve the final result. OCW strives to keep faculty

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**FIGURE 2** OpenCourseWare (OCW) Publication Process. CMS = content management system; IP = intellectual property; QA = quality assurance.
burden to no more than five hours per published course, on average. By contrast, other models of online course publication, such as MOOCs, require a much greater commitment of faculty or teaching team time.

While much of the publication process is fairly routine and mechanical, three elements warrant special mention: intellectual property, accessibility, and archiving.

**Intellectual Property**

The intellectual property (IP) process seeks to manage the use of third-party materials (or “objects”) in full compliance with copyright laws and MIT policies. Such objects might include text, graphics, charts, tables, photos, video or audio clips, software tools, simulations, and other digital resources.

The OCW publication process includes a rigorous scan for third-party objects and a copyright clearance procedure.

It is common for faculty to use third-party objects in their classroom teaching, but publishing such materials, particularly under the OCW Creative Commons license (/terms/#cc), typically requires permission of the copyright holder unless the object is in the public domain. Accordingly, the OCW publication process includes a rigorous scan for third-party objects and a copyright clearance procedure.

Sometimes, objects that meet certain criteria may be used under the fair use doctrine, the right, in some circumstances, to use copyrighted material without seeking permission of the copyright holder and without paying royalties. It is an explicit feature of copyright law in the United States and some other countries. In 2009 MIT OCW collaborated with several other institutions to develop a Code of Best Practices in Fair Use for OpenCourseWare, an important tool to guide practitioners in fair use matters, increase awareness of fair use rights, and reduce risk associated with copyright infringement. The FileMaker tracking system includes detailed records of third-party IP objects used in the course materials and a semiautomated system for emailing copyright owners with permission requests. Objects for which permission cannot be obtained and which cannot be used under the fair use doctrine are replaced or dropped.

**Accessibility**

Accessibility features are added to courses to broaden the reach of OCW to learners with disabilities. For example, materials are formatted and tagged so that they can be interpreted by automated screen readers, and video materials are enhanced with subtitles and transcripts. These features also help students whose native language is not English.

**Archiving**

When a course is updated, OCW consults with the faculty member to determine the disposition of the older version. If it covers different topics or was taught by a different professor in a different way, it is typically maintained with cross-referencing links. If the older version is entirely obsolete, it is archived to DSpace, a digital repository service of the MIT Libraries. Archived courses on DSpace remain accessible via links from the main OCW website. There are nearly 1,000 archived OCW courses.

**Worldwide Distribution**

**OCW Website**

From the beginning OCW has worked with Akamai Technologies, Inc. for worldwide distribution of the OCW website content. The OCW CMS and related websites that feed the Akamai network are hosted on the MIT network. This arrangement has proved to be very reliable and scalable.

**Video Hosting**

In 2008 OCW began delivering video and audio materials through alternative services because of the high bandwidth requirements and consequent high cost of

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6 MIT was among the first major institutions to adopt a Creative Commons license.

using the Akamai services. Today, OCW video/audio
materials are hosted and distributed through YouTube,
iTunes U, VideoLectures.net, and Internet Archive.

OCW video materials comprise thousands of hours
of content, including more than 100 full-course video
lecture series for some of the most popular courses and
supplemental resources, as well as video clips and dem-
onstrations for many more. To date, iTunes U and You-
Tube together have supplied about 160 million video
downloads. These free services replaced bandwidth that
OCW would otherwise have had to buy from Akamai.

Subtitles and transcripts are provided for many OCW
videos, with the capacity for interactive searching based
on the syncing of transcripts and videos, taking the user
to the exact place in the video where the search term
is spoken.

Downloads
Users can download individual courses in zip files for
offline use. Once downloaded, access to the course does
not require an Internet connection. To date, OCW has
delivered about 25 million course downloads.

Mirror Site Program
For users in certain developing regions of the world,
Internet access is cost prohibitive, unreliable, or nonex-
istent. OCW helps bridge the “digital divide” through
its mirror site program.

Since 2006, the program has provided OCW con-
tent on external hard drives, with updates via low-
bandwidth-compatible rsync service, to educational
institutions in areas with limited Internet access. There
are now more than 350 such mirror sites, primarily in
African and South Asian countries such as Ethiopia,
Ghana, Kenya, Namibia, Nigeria, Pakistan, the Philip-
pines, Rwanda, Tanzania, and Zimbabwe.

Local educational institutions become OCW mirror
site affiliates and agree to host OCW materials openly
and freely under the OCW Creative Commons license.
Affiliates also agree to promote OCW use among their
constituents and provide a local contact for content
updates and monthly usage data.

Most OCW mirror site affiliates are colleges or uni-
versities that have good local area networks but may
have access only to costly or weak Internet infrastruc-
tures. Nonprofit organizations, ministries of education,
and Internet service providers are also OCW affiliates.
All technical and coordination efforts are provided on
a volunteer basis.

The program has been greatly facilitated by MIT stu-
dents choosing to serve their home or host countries
and help make OCW available locally. Students on
MIT Public Service Center fellowships or internships
through the MIT International Science and Technol-
ogy Initiatives (MISTI) have personally installed OCW
on local campuses and used the resource to teach cours-
es and topics in mathematics and science.

Translation Affiliate Websites
As described earlier, translated MIT OCW courses are
hosted on their home institutions’ websites.

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Use and Impact

Global Audience

MIT conducts ongoing research and data collection
to evaluate OCW according to the following three
dimensions:

- **Access**: traffic levels (figure 3), users’ educational
  roles and profiles, geographic location, and the tech-
  nical conditions under which they access OCW;

- **Use**: users’ goals in using OCW, what materials they
  use, and their levels of success in accomplishing their
  goals with the materials; and

- **Impact**: impacts of OCW on the lives and experiences
  of users and on educational practices worldwide.

Evaluation is based on techniques and data sources
such as web analytics, surveys, interview protocols,
and user email feedback. Data collection through web
analytics is continuous. A periodic comprehensive user
survey randomly launches from the OCW website,
complemented by occasional surveys of specific audi-
ences and stakeholders.

OCW serves a global audience. As shown in table 2,
nearly 60 percent of OCW website traffic has originated
outside the United States.
For analytical purposes, OCW users are categorized as follows:

- Educators at all levels from high school up (9 percent), who may adopt or adapt the materials for their own teaching purposes; many also use OCW for reference or to enhance their understanding of subject matter.

- Students enrolled in educational programs (42 percent), who may use the materials for reference, practice exercises, mapping out their program of study, or pursuing personal interests.

- Independent learners (43 percent), who find the materials helpful for enhancing their personal knowledge either from the materials themselves or from the many references, readings, and other resources.

- Others (6 percent).

**Use at MIT**

In addition to its service to a worldwide audience, OCW has significant impact on campus at MIT among both faculty and students. The latter use OCW resources such as problem sets and exams for study and practice, and freshmen report that they checked out MIT by looking at OCW before deciding to apply. Instructors often refer students to OCW for part of their coursework as well as in the classroom. Beyond the campus, alumni access OCW materials to continue their lifelong learning and to keep abreast of academic developments at MIT.

Several surveys over the years have consistently indicated that about half of the MIT student population use OCW to select classes. They look ahead to courses and concepts they will study in subsequent years, review concepts covered in previous years, and scan the curriculum to understand how the interdisciplinary challenges they face—whether in studying cancer, climate change, or energy—are addressed in other disciplines. Faculty likewise use OCW to better situate their courses in the curriculum with respect to the course content of their peers, both within departments and across them.

**Open Education Consortium**

Part of the original mission of the OCW project—and a key goal of OCW’s original funders, the Hewlett and Mellon foundations—was to encourage other institutions to follow MIT’s lead in openly sharing course materials. In 2004 OCW began reaching out to other institutions and organizing international conferences on OCW and open sharing. With a few other institutions, MIT launched a prototype of the OCW Consortium in 2005. The original goals were to

- extend the reach and impact of OpenCourseWare by encouraging the adoption and adaptation of open educational materials around the world,
• foster the development of additional OCW projects, and
• ensure the long-term sustainability of OCW projects by collectively identifying ways to improve effectiveness and reduce costs.

In 2008 the Consortium was established as an independent 501(c)(3) nonprofit tax-exempt organization. Later, it broadened its scope to include not only OpenCourseWare organizations, but other types of open education projects as well, becoming the Open Education Consortium (www.oedc.org). Today there are 266 OE Consortium institutions representing 48 countries around the world.

**Future of OCW**

Since the announcement of OCW 15 years ago, much has changed in the world of education, particularly in the areas of digital teaching and learning tools and online access to educational opportunities and resources. As both a dynamic, publicly accessible repository of MIT’s teaching materials and a reflection of MIT’s pedagogical practices, OpenCourseWare plays a central role in placing MIT at the forefront of the open education movement.

As teaching approaches at MIT change, OCW will document and disseminate them, maintaining MIT’s position as a global educational innovator and helping to fulfill its broader mission to advance knowledge and educate students in science, technology, and other areas of scholarship that will best serve the nation and the world.

OCW recently published several MIT courses that have implemented digital learning and new research-based teaching practices to “flip the classroom” and to provide students with interactive online assessments, simulations and visualizations, and access to global classrooms. We anticipate that more OCW courses will include these elements and that OCW Educator will provide a good platform for faculty to share the changes they are making to their classes with colleagues at MIT and around the world.

In these and so many other ways, OCW will continue to advance its mission as it responds to the changes already visible in the future of educational delivery.

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**TABLE 2 OCW users by country, October 2003–December 2015**

<table>
<thead>
<tr>
<th>Country</th>
<th>Total visits</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>82,418,403</td>
<td>41.9%</td>
</tr>
<tr>
<td>India</td>
<td>16,330,775</td>
<td>8.3%</td>
</tr>
<tr>
<td>China</td>
<td>12,487,628</td>
<td>6.3%</td>
</tr>
<tr>
<td>Canada</td>
<td>6,472,152</td>
<td>3.3%</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>6,043,020</td>
<td>3.1%</td>
</tr>
<tr>
<td>South Korea</td>
<td>5,610,569</td>
<td>2.9%</td>
</tr>
<tr>
<td>Germany</td>
<td>3,482,001</td>
<td>1.8%</td>
</tr>
<tr>
<td>Brazil</td>
<td>3,372,826</td>
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<tr>
<td>Turkey</td>
<td>2,856,887</td>
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<tr>
<td>Australia</td>
<td>2,524,836</td>
<td>1.3%</td>
</tr>
<tr>
<td>All others</td>
<td>55,126,234</td>
<td>28.0%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>196,725,331</strong></td>
<td><strong>100.0%</strong></td>
</tr>
</tbody>
</table>
edX and its university partners are working to leverage technologies and innovative teaching methods in order to respond effectively to the changing education landscape.

Nina B. Huntemann

This is a moment when the US, and, I would argue, the whole world, needs to educate more students—partly because we need them to help solve the challenges the world is facing, and partly because education is the most powerful social and economic equalizer.

– L. Rafael Reif, President, MIT

edX is an online learning destination and massive open online course (MOOC) provider founded by Harvard University and the Massachusetts Institute of Technology in 2012. In partnership with more than 90 institutions worldwide, edX now offers more than 900 courses to 7 million learners.

A three-pillar mission guides the edX goals and growth strategy:

• increase access to high-quality education,
• enhance teaching and learning on campus and online, and
• advance teaching and learning through research.

Founded and governed by colleges and universities, edX is the only leading MOOC provider that is both nonprofit and open source.

The Genesis of edX

The idea for edX coalesced during the fall semester of 2011 as then-Provost L. Rafael Reif was thinking big about the future of MIT and higher education in general. Low-cost alternatives that leveraged networked
communication and information technologies were challenging the rising cost of a traditional, residential college education. How MIT would respond to the risks and challenges facing higher education was of keen interest to Reif, and he shared his ideas in conversation with members of the MIT faculty.

At the time, Anant Agarwal, future CEO of edX, was director of the Computer Science and Artificial Intelligence Laboratory (CSAIL) and cofounder of several companies. Like many of his fellow MIT faculty, he works in an environment of experimentation and innovation and is a professor, inventor, and serial entrepreneur. He was also an instructor for the first foundational course in the undergraduate Electrical Engineering and Computer Science (EECS) curriculum, 6.002 Circuits and Electronics, which became the first course offered on edX.

Piotr Mitros, future chief scientist at edX and recent MIT PhD, had been developing ways to blend technology, peer instruction, and education based on his experience developing educational technologies for use in Africa. He too had cotaught 6.002 in an experimental version based on project-based learning guided by industry mentors. In a moment of serendipity, the three came together. Reif and Agarwal had been faculty in the same department, and Mitros had worked for both of them as a graduate and undergraduate student.

From the First Course to 90 Global Partners

Mitros developed the software that would become the framework for the edX platform, called MITx. The first course was an experimental online adaptation of Circuits and Electronics, renumbered 6.002x and cotaught by Agarwal, Professor of Electrical Engineering Gerald Sussman, EECS Senior Lecturer Chris Terman, and Mitros. The course was made available in February 2012 to MIT students enrolled in the residential 6.002 as a blended learning experience. Enrollment for online learners opened in March. When the 6.002x session ended in early June, more than 150,000 students from around the world had enrolled.

The positive response from both on-campus and online students led MIT and Harvard to expand MITx to a nonprofit enterprise delivering online courses from top universities around the world.

Historical Innovations in Open Education and Content Delivery

When Harvard and MIT announced the formation of edX, the unprecedented partnership between two of the world’s best universities set out to advance an enduring principle: open education. The central idea behind this principle—that access to education is a necessary condition for personal, economic, and social progress—has undergirded education initiatives for centuries.

From the Middle Ages to the Renaissance

Sandra Peter and Markus Deimann (2013), scholars of the history of adult education, trace early forms of open education to Europe in the late Middle Ages, when citizen demand for access to knowledge outside the monastery walls increased with urbanization and migration. This period was followed by the rapid expansion of colleges and universities throughout Europe.

But the institutionalization of higher education during the 15th century included the collection of fees from students, closing access to many. Contemporary critics of higher education claim that the current crises faced by many colleges and universities, particularly in the United States, “can be found in the fate of medieval universities” (DeMillo 2011, p. 126).
Yet even as access to formal, institutional education was closing, the Gutenberg press, public libraries, and self-organized and informal social learning contributed to a renaissance in open education in the 16th and 17th centuries, at least for the literate male populace (Peter and Deimann 2013).

The 19th and 20th Centuries

In the United States, the Morrill Acts of 1882 and 1890 established land-grant colleges and universities to provide access to education as a public service to a growing population (Scott 2006), and the public university system became an anchor for expanding educational opportunities.

The Smith-Lever Act of 1914 created a partnership between land-grant universities and the US Department of Agriculture to provide rural citizens with the latest methods in farming and home economics. A key success of the program was its delivery method: home or community-based instruction. Educators created instructional materials and curricula based on agricultural research conducted at state universities, and brought this knowledge to farmers through community demonstrations and home-based tutorials (Fiske 1989).

Across the Atlantic Ocean, the United Kingdom pioneered open access to higher education by leveraging the cutting-edge technology of its time: broadcast television. Beginning in the 1920s, the UK delivered educational content through the British Broadcasting Corporation’s radio and television network.

Then Britain’s Open University, established in 1969, added the credential of a college degree to the national broadcast tradition in order to bring “high-quality, degree-level learning to people who had not had the opportunity to attend traditional campus universities” (Open University 2016). The first course it offered was in introductory math. The course aired on BBC channel 2 in January 1971 with 25,000 registered students and 100,000 more tuning in to watch the program.

In the United States, local broadcast television and radio stations, and later cable television systems, were mandated to offer some community-focused educational services in the decades before broadband Internet access, though these programs rarely provided a focused curriculum.

Open Platforms for Open Education

OCW

Ten years before edX put its first course online, MIT president Charles M. Vest announced a bold initiative to post all of the university’s course materials on the Internet for
free (see Miyagawa in this issue). The MIT OpenCourse-Ware (OCW) project made videos, lecture notes, audio recordings, images, and other course materials used in MIT residential courses available online. At the OCW site (ocw.mit.edu), a student can browse—as in a library—thousands of course materials from MIT professors, making the site an excellent resource for the self-directed learner.

In 2002 OCW posted its first 50 courses and a year later had over 500 courses available. As the New York Times reported, MIT chose the path of free and open when many higher education institutions, college course providers, and textbook publishers were looking for a for-profit business solution to deliver content online (Goldberg 2001).

Like the Open University before it, MIT blazed the trail for open access to education by providing university course content for free, and OCW was the foundation for MITx.

**edX Innovations**

MIT did not, however, offer either access to professors or certificates for completing courses. The innovation that edX has contributed to the advancement of open access to education is the expansion of content to include courses and certification, delivered on an open source platform designed for global scale.

The next step in opening access to education was to make available not just the courseware (content), as OCW had accomplished, but to open the course itself to a world of learners by providing access to the instructor and creating opportunities for peer learning. Thus educational experiences on edX include the course content (e.g., videos, lecture notes, images), instructor-learner and learner-learner interactions (e.g., discussion forums, peer review), and learner outcomes (e.g., graded assignments, certification).

The MITx prototype platform was built to be flexible so professors and universities could design courses in ways that not only accommodated and reflected the pedagogy of the instructor and the institution but also supported improved methods of teaching and learning. To encourage diversity of instruction, various types of assignment and assessment were provided.

The edX platform has evolved to include additional assignment and assessment types, the XBlock component architecture that enables developers to create independent course components and share them with the edX community, and learning tool interoperability (LTI) so that course developers can add educational materials from third-party providers.

**edX has advanced access by including courses and certification, delivered on an open source platform designed for global scale.**

Included in Open edX is the course authoring software Open edX Studio; the Open edX learning management system (LMS) that learners use to access course content; the XBlock component architecture; the ORA2 XBlock, which implements an open response assessment problem type; the discussion forum architecture; Open edX Insights, a course analytics tool; and mobile application and ecommerce components.

The public collaboration of the Open edX community returns benefits to the platform as well, as edX member institutions and many unaffiliated organizations have contributed significant platform features. These enhancements include improved hinting from Stanford University, single-sign-on from Google, and a peer instructor XBlock from the University of British Columbia. Open edX also fosters a growing ecosystem of third-party service providers, such as OpenCraft, Extension Engine, Appsembler, eduNext, and IBL Studios.

**Global Spread of edX**

The edX platform was made available on June 1, 2013, and today is used all over the world to host MOOCs as well as blended residential courses and training modules. Universities, national consortiums, nonprofits, and professional education firms have created Open edX sites. As of January 2016, there were over 200 known instances of Open edX installations running and available online in over 30 countries, hosting more than 3,000 courses.

Offering the edX platform code to the world for free empowers educators to experiment, innovate, and share new methods of teaching, and these lead to improvements in learning.

**A “Particle Accelerator for Learning” and Research**

To advance teaching and learning through research—one of the three pillars of its mission—edX makes
available to member institutions the anonymized learner event data for the millions of learner clicks and page views captured on the platform. From this data package, edX member institutions can design and execute complex learning analytics research. In the 3½ years since edX formed, research projects using data from edX-hosted MOOCs have been presented at and/or published in leading education, technology, and learning science conferences and journals.

In addition to the data package, a tool in the edX platform called Insights provides course teams with daily data about learner activity, background information, and performance throughout the course. Using edX Insights, instructors can monitor how learners are doing in their courses and evaluate their instructional design and assessment choices. Anyone with administrative or staff access to a course can see enrollment activity, such as when and how many students are enrolled, and the geographic location and demographics of students. Learner activity metrics are presented for engagement with course content and accompanying videos, as well as the performance distribution of students across graded and ungraded assignment submissions. These capabilities provide instructors with real-time actionable feedback about the efficacy of their instructional materials and assessments.

For more complex analysis, content experiments—also known as A/B or split tests—can be set up for a course, enabling teachers and researchers to compare the effectiveness of course content by analyzing differences in learner performance. Multiple content experiments for multiple groups of students are possible in a single course, and the edX platform assigns learners to experiment groups in random, evenly distributed configurations.

MOOCs have facilitated a new field of learning science research based on big data. Agarwal describes the opportunity as a “particle accelerator for learning” (Stokes 2012). edX will continue to participate in and contribute to this growing research community, with platform capabilities that support research and analysis to advance teaching and learning both online and on campus.

The Future of Open

When MOOCs gained public awareness in 2012, prognosticators enthusiastically or apocalyptically declared that the courses signaled the downfall of institutions of higher education. It is certainly true that colleges and universities, particularly in the United States, are facing challenges to their enrollment, finances, and reputations at a level of intensity and pace that many have never experienced before. MOOCs are neither the lone cause of nor the sole solution to these difficulties.

edX and its university partners are working to leverage the technologies and methods that teaching and learning at scale afford in order to respond positively and productively to the changing education landscape. At the core of this response is a commitment to open access education that will serve lifelong learners around the world.

Opening educational access in the digital age depends on creating a more porous university where learners can have affordable, high-quality educational experiences throughout their lives from multiple institutions in a diversity of formats—online, on campus, and blended (Smith 2015). The more opportunities learners have to achieve their educational goals, the greater capacity the world has to solve the challenges it faces.

References

A continuous research infrastructure for MOOCs will enable more rapid improvements in online teaching and learning.

Engineering the Science of Learning
Developing a Continuous Research Infrastructure for MOOCs to Catalyze Learning Research

Justin Reich

Four years since the creation of Coursera and edX, there is much to celebrate in the accomplishments of research into massive open online courses (MOOCs) and other forms of open online learning.

Millions of students have participated in thousands of courses, leaving a trail of billions of log events recording their behavior, efforts, failures, and successes. From these massive records, researchers have documented the demographic characteristics of learners and patterns of course participation (Ho et al. 2015; Perna et al. 2014), and they have begun exploring methods for supporting greater persistence and completion in courses (Baker et al. 2014).

But, for all the very useful, policy-relevant findings, MOOC research has led to few new insights about how people learn and how best to support their learning. Beyond basic observations that more active students earn higher grades than less active students, there are few new theories or design principles for how students learn best or how best to teach them.

To take advantage of the opportunities for research provided by the millions of students across thousands of MOOCs, an ambitious new approach to online learning research is needed.

How to Enhance Online Learning Research
Large-scale online learning environments should be engineered so that both the learning platform and courses are continuously improving. Internet
services such as Google, Facebook, and Netflix regularly test new features and experiences with users, and this steady stream of experimentation provides evidence and insights that allow these services to iteratively improve.

Three changes, already under way in pockets, are necessary in MOOC platforms and course development processes to support constant development.

First, cycles of course offerings should be dramatically shortened by shifting from session-based courses that run once or twice a year during specific dates to on-demand courses that allow new cohorts of students to start every week or even every day. Several of the world’s largest courses with over a million registrants each—Harvard’s CS50X: Introduction to Computer Science, Stanford’s Machine Learning on Coursera, and UC San Diego’s Learning How to Learn on Coursera—have adopted this approach, and Coursera has been refactoring its platform to support these kinds of on-demand courses. The shift to more flexible availability will allow insights from experimental interventions to be incorporated more rapidly and regularly and accelerate the pace of learning research as courses iteratively improve.

Second, MOOCs need to incorporate an expanded set of experiments, so that each course tests a variety of instructional approaches—from the overall syllabus design to the specific wording of questions and prompts. Every course should be designed and implemented in such a way that it collects evidence to make the next run of the course better. edX has recently introduced authoring tools that make it very simple for any course developer to include randomized experiments (sometimes called A/B tests) that test the efficacy of different pieces of course content.

Third, to take advantage of these platform changes, course teams will need to include greater multidisciplinary expertise and to more tightly couple the work of course designers and researchers. Rather than having faculty and course teams create courses to be evaluated afterward by separate research teams, research considerations should be built into courses from the earliest phases of design. In the days before MOOCs, the Open Learning Initiative (OLI) (formerly at Carnegie Mellon and now at Stanford) pioneered this kind of joint development among researchers, software developers, and content experts (EDUCAUSE Learning Initiative 2006).

With these changes to platform and processes, MOOCs would support a continuous research infrastructure. It would be continuous in two ways.

1. Learning research would be an important consideration throughout every phase of course design, deployment, and refinement. At present, course design and education research are pursued separately, and research occurs as a phase in the course life cycle after the development of the course, usually by a separate team. In a continuous research infrastructure, research considerations would be attended to from the earliest days of proposing a course through its final archival as static open courseware.

2. Courses—with their embedded experiments—would run on an always-on, on-demand basis rather than once per year. At present, annual cycles of course offerings mean that iterative improvements based on the results of instructional experiments require years to come to fruition. In a continuous research infrastructure, on-demand courses would allow for tighter (shorter) cycles of iterative improvement, guided by evidence from constant experimentation.

More flexible availability in online courses will allow insights from experimental interventions to be incorporated more rapidly and accelerate the pace of learning research.

With these major shifts, MOOCs will be better positioned to improve in quality and advance the science of learning as they make learning opportunities available to the public.

In the following sections I review limitations in current MOOC research, and then discuss the three shifts—on-demand courses, expanded experimentation, and multidisciplinary design teams—necessary to realize a more ambitious future for large-scale online learning research.

A continuous research infrastructure for MOOCs will support shorter and more integrated cycles of instructional experiments, analysis of student learning data, and refinement of existing courses, and these shorter
cycles of experiment and iteration will enable more rapid improvements in online teaching and learning.

**Limitations in Current MOOC Research**

MOOC research is currently defined by the separation of course development from learning research. In typical, nearly universal practice, course developers and researchers are two separate teams engaged in two different, overlapping initiatives: faculty and instructional designers make courses, and researchers study the results afterward.

"Fishing in the Exhaust"

I have characterized the early years of MOOC research as “fishing in the exhaust,” a strategy in which instructional teams create MOOCs without regard to research objectives or questions, platforms log data from student behavior in those courses, and data analysts examine the tracking log data, the “exhaust,” afterward (Reich 2014b).

There was optimism in the basic outlines of this strategy. An early hope of MOOC enthusiasts was that the reams of data collected by online learning platforms would enable an almost purely inductive approach to learning research (Nihalani 2013; Norvig 2015). Once educational researchers and their computer science partners had “the data,” data mining tools and predictive algorithms would bring educational research into the modern era. Algorithms would unlock the secrets to human learning hidden in these data.

But in these first years of MOOC research the strategy has primarily yielded commonplace findings about MOOC student behavior. In a paper about MITx’s first course, 6.002x (Circuits and Electronics), DeBoer and colleagues (2014) examined 20 activity and outcome measures and found that each form of activity was positively correlated with every other form of activity. Thus, the number of lectures watched is positively correlated with the number of forum postings, both of which are positively correlated with the numbers of hours on site and of weeks active, and all of these are positively correlated with grades and certificate attainment.

Dozens of studies along the same lines followed, many of them reaching similar conclusions. I have summarized this observation as Reich’s Law: “People who do stuff do more stuff, and people who do stuff do better than people who don’t do stuff” (Reich 2014a). A substantial portion of the MOOC research literature to date can be summarized thus.

**Data, Quality, and Assessment**

The research has been limited because the systems generating the data are limited. MOOC instructional materials are not designed to test multiple instructional approaches, beyond perhaps presenting some material in multiple media, such as text and video.

They may be of low instructional quality as well. In a recent study of MOOCs’ alignment with generally accepted principles of instructional design, the scores of 76 MOOCs ranged from 0 to 28 on a 72-point scale (Margaryan et al. 2015).

Moreover, assessment materials are plagued by technical limitations—virtually no MOOCs attempt automated assessment of sophisticated human performance like essay writing or design exercises. There are a few interesting trials of peer assessment of complex performance (e.g., Kulkarni et al. 2015), as in Scott Klemmer’s Human Computer Interaction course (https://www.coursera.org/learn/human-computer-interaction), but most MOOCs include only multiple choice or quantitative response questions.

The assessment infrastructure in many MOOCs does not support robust inferences about what students do and do not understand. If outcome measures don’t provide adequate evidence of what students have learned, and if input materials provide a limited range of instructional supports, prediction algorithms will at best find a local minimum. Future systems with more sophisticated instructional approaches and richer measures of learning will yield more useful results.

**Separation of Course Development and Experimental Design**

Post hoc observational research has been accompanied by a smaller set of experimental studies (Anderson et al. 2014; Kizilcec et al. 2014; Lamb et al. 2015). They have
been very important in pointing the way toward a future paradigm of experimentation in MOOC research, but their limitations are also instructive.

As mentioned above, most MOOC experiments have been designed and implemented separately from course development teams: one common model is that a team of social psychologists or behavioral economists develops an intervention that can be dropped into any course for testing. Because the researchers have no content expertise, few published experiments have been based on discipline-specific educational research or attempted to improve subject-specific instruction.\footnote{An experiment in the first version of CopyrightX in 2013 stands out as an exception: it tested two different curricula, one based on US law and one based on international examples (Fisher 2014).}

In addition, few lines of experimental research have iteratively tested refined intervention designs over multiple cycles, in part because the course cycles are so long: If courses run only once a year, then every iteration of an intervention requires a year of delay to be implemented and evaluated. MOOC experiments have yet to take advantage of the massive numbers of learners or the full potential of a shift to digital learning infrastructure.

Fishing for correlations in course tracking logs and implementing simple one-off experiments were both sensible initial approaches to exploratory MOOC research. Creating separate course creation and research teams worked neatly for most university organizational structures, and the platforms offered minimal support for in situ or iterative experimentation.

For the field to advance, however, early efforts must not rut out into path dependencies (Reich 2015). A shift to continuous research infrastructures would address many of the limitations of the current paradigm. The course development process needs to attend to research continuously throughout the creation of new courses, and platforms need to support continuous, iterative experimental research.

### From Session-Based to On-Demand MOOCs

Borrowing from the heritage of residential education, the earliest MOOCs typically had defined start and end dates, often mirroring the traditional semester calendar. But this approach is inconvenient for the busy and complicated lives of online learners who may not be full-time students.

### Redefining Course Cohorts

MOOC platforms need to enable courses that can be run continuously with on-demand signup. Coursera has made substantial progress toward this shift. Many of its most popular courses now have sessions that begin every two or three weeks rather than once per year.\footnote{edX does not provide platform support for on-demand courses, so CS50x (Introduction to Computer Science) runs from January 1 through December 31 each year, and as the year progresses the recommended schedule of deadlines automatically updates, albeit for all students rather than in a personalized way.}

#### Few published experiments have been based on discipline-specific educational research or attempted to improve subject-specific instruction.

When courses start every few weeks, multiple instances of a course are running in a staggered fashion, allowing 10–25 new cohorts per year instead of only one or two. Course interventions can go through multiple iterative cycles each year, and if research proceeds quickly enough it could even be possible to introduce effective interventions to existing cohorts, so that students more rapidly receive the benefits of their participation in experimental activities.

It may ultimately be possible to allow for course cohorts to be segmented not by when students start but by where they have progressed in the course, so cohorts are defined by each student’s last activity rather than the time of their first. Evidence from student tracking logs suggests that heterogeneity in course completion pathways is high (Mullaney 2014) and in some courses very few students maintain the recommended schedule (Mullaney and Reich 2015).

### Drawing from Online Games

One effective model of progress-based cohorting occurs in massively multiplayer online games that provide tools for characters of different levels and abilities to
find appropriate synchronous challenges on an on-demand basis. Players use “Dungeon Finders” that help algorithmically assemble groups of similarly leveled, currently online players ready to take on the same challenge (Dabbish et al. 2012).

In MOOCs, problem set discussions and synchronous debates would replace raids and dungeons, but the mechanisms for cohorting students on-demand for particular kinds of challenges might be similar (see Ferschke et al. 2015 for two prototypes). With these kinds of tools in place, it might be possible to target an intervention at a particular point in a course (a topic, discussion, or assignment) and gather data from all students progressing through that section over a period of days rather than months. This kind of model would look much more like the on-going experimentation conducted by Google and Facebook than the annual research cycles more typical of classroom educational research.

It might be possible to target an intervention at a particular point in a course and gather data from students over days rather than months.

Supporting Sophisticated Experimentation

For continuously running courses, platforms need to develop the infrastructure to support sophisticated experimentation. edX offers basic tools for authoring A/B testing of content blocks in courses, and Coursera plans to release similar functionality. These tools allow nonprogrammers to implement randomized controlled trials of course content with the same ease with which they would add a reading, video, or assignment.

Student “Self-Check”

In one recent experiment, HarvardX course developers and researchers tested a voluntary “discussion self-check,” a noncredit question on quizzes that asked if people had contributed to the forum (Lamb et al. 2015). The goal was to encourage greater forum participation. With each weekly quiz for the first six weeks of the course, one random half of students received the normal three-question quiz, and the other received the three questions plus the self-check question (this kind of design might be better understood as an A/Not A test rather than an A/B test). Findings showed that the group that got the self-check question contributed new forum posts at about twice the rate of the control group. As a result, discussion self-check questions are increasingly a common feature in HarvardX courses.

The edX experimentation toolkit is a great start but has a limited palette of options for experimental design. Researchers can set up A/B or A/B/.../N tests at the content block level but not at the chapter or unit level. It is also not possible to experiment with the overall structure of the course or the interface of the platform. All students are randomly assigned in equal proportions to all groups, whereas more sophisticated assignments through matched pairs (King et al. 2011) or dynamic assignments through multi-armed bandits (Scott 2010) would allow for a more robust range of experimental designs.

With a more diverse toolkit, researchers will be able to expand the number and kind of experimental interventions in each course. In a continuous research infrastructure with large numbers of students, researchers should lean toward including larger numbers of multifactorial experiments in MOOCs. For instance, in the discussion self-check experiment, only one version of the intervention was tested with nearly 10,000 students in each treatment and control group. A substantial amount of statistical power was, in a sense, wasted. Researchers could have tested different question stems, response anchors, question placements, and other features of the self-check to better understand the mechanism of the intervention and to optimize its effect.

Power Calculations

In typical classroom education research, power calculations are used to determine whether a study has sufficient numbers of subjects to make reasonable claims; in MOOC research, power calculations should be used to estimate how many different experiments can be fit into a course. In contrast to the “correlate everything with everything else” approach to post hoc observational research and the “try one thing and modify every year” approach to typical experimental research, researchers in a continuous research infrastructure should pursue a targeted set of theory-informed experiments, with large numbers of content and sequential variations, continuously updated from one weekly cohort to the next as new findings emerge (Williams and Heffernan 2015).
Each modification on particular interventions might result in trivial gains in learning outcomes—a slight improvement in explanatory text might result in effect size gains of only 1/100 of a standard deviation. In the typical approach to educational reform, such gains are seen far below the threshold of useful interventions to pursue, as defined for instance by the .25 effect size threshold for inclusion in the Institute of Education Sciences (2014) What Works Clearinghouse. Such high thresholds for worthwhile interventions are appropriate for reform efforts that require substantial time and commitment to implement.

In a continuous research infrastructure, it may be possible to string together 25 interventions with .01 effect size to produce meaningful gains in student learning, if at least some of the 25 effects are additive. If each intervention requires only a few minutes of programming to implement and can then be delivered with perfect fidelity to every subsequent student, then the cumulative effect of small interventions on student learning could eventually be quite substantial. Rather than seeking a single “home run” intervention, continuous research infrastructures seek to codify large numbers of small improvements that can build on one another.

**Course Instructional Teams**

To take full advantage of these more sophisticated platforms, courses will need to be designed from the beginning to answer specific research questions and course teams will need to include a greater range of multidisciplinary expertise. The current research model depends on a kind of serendipitous insight—that across dozens or hundreds of courses there are good ideas being baked into the instructional design of courses that predictive algorithms will be able to identify post hoc. A more promising approach is to design courses to answer the most important educational questions in a discipline.

**Need for Multidisciplinary Teams**

Diverse expertise is required to develop courses as spaces for systematic research. Course teams should include content experts and discipline-based education researchers who can identify relevant dilemmas in disciplinary instruction and propose competing approaches to resolve them.

Instructional designers are needed to incorporate effective pedagogical approaches in the online platform. Experts in causal research methods and experimentation should ensure best practices in randomization, experimental design, and data collection for analysis. Others with experience in assessment design need to develop an assessment infrastructure that measures student learning outcomes that are relevant to course goals and research questions.

Teams may require software developers who can implement new approaches to assessments or instruction. As the course progresses through daily or weekly cohorts, data scientists need to identify promising instructional approaches and areas for modifying and improving interventions.

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**Instead of a single “home run” intervention, continuous research infrastructures seek to codify large numbers of small improvements that can build on one another.**

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The Open Learning Initiative has used a version of this multidisciplinary model for years in its course development (EDUCAUSE Learning Initiative 2006). One of the signature advantages of this approach to course design is that content experts often suffer from a “curse of expertise” (Hinds 1999)—they lose the ability to empathize with new learners and to predict the kinds of learning scaffolds that novices need in a new subject. Working in diverse teams ensures that course faculty have design partners who can represent the voice of content novices throughout the design of the course.

**Organizational and Cultural Shift**

While to some extent team experts may be able to work in a temporal sequence, a major organizational shift would enable close collaboration among the experts during the course design phase. Ideally, as universities evaluate faculty and courses for funding, courses with clear research goals would be given both priority in the approval process and additional funding.

“Research-focused” courses should be developed using a new, separate process that ensures that both learning goals and research goals are well defined from
the beginning of course development and that various course elements align with those goals. Overall, universities might concentrate their resources to produce fewer and better courses.

These changes call for faculty to accept a profoundly different role as teachers. Rather than the current “one-man band” approach, where faculty serve as designers, presenters, assessors, and evaluators, faculty would join a team to carry out these roles. In exchange for diminished autonomy over every aspect of the course, faculty would get access to greater resources in creating a course and the opportunity to participate in systematic investigations into teaching and learning.

Some future MOOCs might be led by a new kind of faculty member whose primary purpose is leading these kinds of complex endeavors, or senior faculty might be released from teaching and service responsibilities to focus on a single course for an extended time. It is unclear how many current faculty would be eager to accept such a trade, but given the scale and cost of building MOOCs in a continuous research infrastructure, only a relatively few pioneers would be needed.

Funding and Incentivizing a Continuous Research Infrastructure

The proposed additional effort and expertise will make the development of MOOCs more expensive than the process is currently. Current expense levels, however, typically allow for substantial investment only in a “first draft” of MOOC materials and then course teams are required to turn their attention to new a project. These first drafts are of mixed quality, do not improve much between runs of a course, and many do not appear to be sustainable to produce over the long run (Hollands and Tirthali 2014).

While there may be value in dozens of new first-draft courses each year, to identify which topics will garner an audience, this rapid generation should be complemented by a smaller set of courses with much greater investment and improvement over a longer period of time. Developing a continuous research infrastructure for online learning will require substantial new funding to support platform upgrades and larger teams working together for longer periods of time, all of which will ideally be justified by more valuable research findings, better learning experiences for students, and a greater return on investment for universities.

Justifying Investment

There are at least two potential approaches for justifying the additional level of expense. One would be for universities and MOOC providers to lavish this level of attention on their highest-revenue-generating courses, in the expectation that greater learning, satisfaction, persistence, and rates of completion would raise the bottom line of profitable courses and provide a monetary justification for the higher expenses. The intersection of research and financial interests could prove to be quite powerful; the model appears to be the approach motivating Coursera’s Course Success Team (Riddell 2015).

A second approach would focus on “public good,” with the same level of attention brought to bear on the most commonly taken courses. Such a model would borrow inspiration from Rice University’s OpenStax initiative (Baraniuk 2013), which has created open source textbooks for the 20 college courses with the highest cumulative enrollment (mostly introductory courses in math, physics, biology, chemistry, history, and social sciences).

Philanthropists could justify investment in a continuous research infrastructure for these courses not only because they have the potential to benefit the large number of MOOC students but also because the research insights from careful analysis of these courses would benefit all introductory instruction in the discipline.

Incentivizing Faculty

Any discussion of efforts to improve teaching in higher education inevitably comes around to the challenges of incentivizing faculty to devote their scarce time and energy to teaching and discipline-based education research. Dedicated streams of funding can be one mechanism to unlock faculty time for such research to improve instruction.
Some science and engineering departments are also creating new positions, such as professors of practice, to retain faculty more committed to teaching than research. These teaching-focused faculty may be the ideal leaders for new courses based on a continuous research infrastructure.

In many disciplines and fields, education research is growing as a legitimized domain for scholarly inquiry—such as the physics education research community—with specialized conferences, journals, and recognition in tenure and promotion decisions. Nurturing the growth and prestige of these scholarly communities will, in the long run, be among the best ways to support faculty committed to advancing teaching and learning research in STEM fields.

**Conclusion**

The elements of a continuous research infrastructure for MOOCs already exist across platforms and organizations. The Open Learning Initiative offers a model multidisciplinary design process, Coursera has pointed the way to large-scale, on-demand MOOCs, and edX has implemented the most user-friendly interface for nonprogrammers to implement A/B testing in a learning management system.

The challenge is to weave these pieces together—in terms of both the technological platform and the social organization of course design—to create courses that are engines of research, learning, and improvement. Internet companies in the private sector have demonstrated the capacity for iterative development in online services through constant experimentation and refinement. Universities and their MOOC platform partners should apply these insights to the emerging platforms of online learning.

Rapid and opportunistic expansion of MOOC research has made clear the tremendous potential of the enterprise, and the next era should be characterized by a targeted focus on building the infrastructure that will allow MOOCs to more effectively advance the science of learning.

**References**


The flexibility of student pathways in today’s university programs can make it difficult for students to perceive the relationships between the courses they take and to integrate their knowledge and skills in a useful way. In this paper we describe a tool we have developed to help students cope with this challenge.

**Crosslinks**

**Improving Course Connectivity Using Online Open Educational Resources**

Haynes R. Miller, Karen E. Willcox, and Luwen Huang

Crosslinks provides a way to organize access to OERs while helping students recognize links between the various subjects they study.

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The flexibility of student pathways in today’s university programs can make it difficult for students to perceive the relationships between the courses they take and to integrate their knowledge and skills in a useful way. In this paper we describe a tool we have developed to help students cope with this challenge.

**Background**

A student progressing through a university curriculum often experiences a lack of connectivity among courses. For example, third-year courses tend to assume facility with methods learned as a first-semester freshman, but as

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textbook ownership declines,\(^1\) the problem of refreshing old knowledge gets more complicated. Conversely, first-year course lecturers often assume either that the material is intrinsically interesting (as it often is for them), or that the students know in advance how important it will be later in their studies.

The Massachusetts Institute of Technology (MIT) is just one example of an institution where these problems occur. Although MIT offers core courses in science, mathematics, engineering, and technology (STEM) constituting part of the school’s General Institute Requirement and taken (or examined out of) in one form or another by all students, such disconnects are often observed, especially in the transition from core science classes to downstream engineering classes.

The Crosslinks website (crosslinks.mit.edu) is editable by anyone with MIT authentication credentials and open and freely accessible to all. We invite readers to explore it on their own.

**What Is Crosslinks?**

Crosslinks is a network that represents the relationships among topics and that connects topics to OERs. The nodes in the networks are topics, and the links represent prerequisite or co-requisite relationships between topics, grouped under five facets of learning, each describing the function of an educational resource:

- **Prepare**—prerequisite topics for review, enabling the student to identify “gaps” and critical points in her abilities
- **Relate**—closely related topics that tend to be learned together
- **Learn**—resources (e.g., course notes, modular videos, mathlets) where the topic might first be learned or that can serve to refresh knowledge or understanding
- **Advance**—topics that follow the current one, enabling the student to better grasp the context for the current topic
- **Apply**—links to interesting applications of the topic in later courses or in industry or other professions; answers the question, “How is this useful in the real world?”

Each topic has a Crosslinks webpage, which is structured in a uniform way. Figure 1 shows a snapshot of the Crosslinks page for the topic Integration by parts. After a brief phrase describing the concept, along with links to external definitions (such as those in Wolfram MathWorld or Wikipedia), the page provides links related to the topic.

In populating the topics, we focused on basic concepts that tend to be taught in one subject, or by one department, and used in other follow-on subjects, frequently in other departments. As of the writing of this article, Crosslinks features 340 topics from 18 subjects across six departments at MIT.

Figure 2 shows a representation of a sample topic network. Each node represents a topic in the Crosslinks collection. The size of the node indicates the number of topics that link back to this node—the larger the node, the more foundational the topic.

The links between nodes indicate **Prepare-Learn** prerequisite relationships. In the example depicted, a mouse

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1 See Griffiths and Maron in this issue.
Integration by parts

Integration by parts states that if \( u = u(x) \) and \( du = u'(x) \, dx \), while \( v = v(x) \) and \( dv = v'(x) \, dx \), then:

\[
\int u(x) v'(x) \, dx = u(x) v(x) - \int v(x) u'(x) \, dx
\]

--- Wikipedia

\[\text{Integration by parts} \rightleftharpoons \text{Integration by parts}\]

\[\begin{array}{c}
\text{Prepare} \\
\text{Product rule} \\
\text{Definite integral}
\end{array}\]

\[\begin{array}{c}
\text{Learn} \\
\text{MIT 18.01 Single Variable Calculus: Lecture Notes} \\
\text{MIT 18.01 Single Variable Calculus: Video Lectures} \\
\text{18.01SC Single Variable Calculus: Integration by Parts Video} \\
\text{18.01SC: Single Variable Calculus: Integration by Parts Practice} \\
\text{Khan Academy Videos and Exercises: Integration by parts formula derivation and examples} \\
\text{UC Davis Integration by Parts definition and practice problems}
\end{array}\]

\[\begin{array}{c}
\text{Relate} \\
\text{Reduction formulas}
\end{array}\]

\[\begin{array}{c}
\text{Advance} \\
\text{Fourier series} \\
\text{Laplace transform} \\
\text{Finite element method}
\end{array}\]

\[\begin{array}{c}
\text{Apply} \\
\text{Math 54 (MIT Summer Course): Fourier Series and Integration by Parts} \\
\text{18.303 Linear Partial Differential Equations: Problem Set (see Problem 1b)} \\
\text{16.901 Computational Methods in Aerospace Engineering: Lecture on the finite element method}
\end{array}\]

FIGURE 1  Sample Crosslinks web page. Each such page includes a brief description of the topic and then links to open educational resources and to other topics, organized by the five sections of Prepare, Learn, Relate, Advance, and Apply.
over the topic **Simple Harmonic Oscillator** highlights the paths of prerequisite topics: Ordinary Differential Equation, Hooke’s Law, and Newton’s 2nd Law. These in turn depend on others, tracing back to the topics of Limit, Vector, Free-body diagram, and Taylor series.

This example illustrates an important aspect of the Crosslinks project: There are multiple possible representations and interpretations of learning pathways. The linkages represent the views of the student contributors, which are often (but not always) formed by the particular way a topic is presented in their classes.

At MIT, the simple harmonic oscillator is the foundation of the mathematics class 18.03: Ordinary Differential Equations. But vectors enter only tangentially (and normally); the matrix exponential is not directly connected to the mathematics of the harmonic oscillator, and while it is certainly an important part of the course it is not introduced by means of the Taylor series.

In contrast, a follow-on engineering class in dynamics or control might link these topics in different ways; for example, engineering classes often introduce the matrix exponential using the Taylor series. Students’ view of linkages between topics thus involves some synthesis of their individual learning experiences.

In some cases, we found that faculty and students did not agree on the linkages represented in Crosslinks. Rather than worrying about publication on the site of learning pathways that are “wrong,” we view this as an opportunity to explore student conceptions and misconceptions about the relationships among topics.

Divergences among student and faculty perceptions of linkages are also an excellent opportunity for faculty to discover connections across topics inferred by students, which, as disciplinary practitioners, we perhaps did not appreciate. This point does, however, indicate the need for some faculty curation and oversight to help vet the site’s content. As with any wiki, the development of Crosslinks depends on contributions from all levels of expertise.

A related challenge occurred in the creation of the topic description. In our initial implementation, we created this piece of material (all other Crosslinks content is external links). This proved to be quite difficult and contentious—and indeed revealed a number of student misconceptions. In the current Crosslinks implementation, for this brief description we quote the lead sentence from the corresponding Wikipedia entry or some other authoritative source.

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**Crosslinks Conception and Design**

The origins of Crosslinks can be traced to sustained efforts by the first two authors to better connect mathematics and engineering material taught across departments at MIT.

Miller had taught the basic ordinary differential equations class 18.03 for several years; it was taken by around 85 percent of MIT undergraduates and by virtually all engineering majors. He felt strongly that two-way communication with the engineering faculty was essential to make this class worth the enormous effort it took to run it. He asked engineers what parts of the subject were particularly important in their courses for which 18.03 was a prerequisite, and he sought good examples to enliven the mathematics. Conversely, it was important that these faculty know what was actually covered in 18.03 and how, so that they could meet their students where they were as they began their engineering studies.
Willcox, upon joining the MIT faculty as an assistant professor, was alarmed at an apparent lack of mathematical preparation of her aerospace engineering students and a lack of awareness among her faculty colleagues of what was taught, and how, in prerequisite mathematics subjects. She set about organizing a study of the flow of mathematical topics from math courses into and through the aerospace engineering major (Willcox and Bounova 2004).

The Crosslinks project emerged from a collaboration between the two of us. It was officially launched in 2010, thanks to support from an MIT Alumni Funds Grant. In addition to the two of us, the founding team comprised Heidi Burgiel, a professor of mathematics at Bridgewater State University on sabbatical leave at OCW, and Chad Lieberman, a former MIT undergraduate who at the time was working with Willcox as a graduate student.

Guiding Principles
The initial design of Crosslinks was informed by several principles:

• The primary target audience was MIT residential students.

• While initial motivation was drawn by connecting our own classes in ordinary differential equations and aerospace engineering, we envisioned the list of topics growing to cover other curriculum areas.

• We did not want to get into the business of producing new explanatory text; we wanted to use existing material.

• Similarly, we did not intend to create any new learning resources; we simply wanted to link to existing OERs.

• Links included in Crosslinks needed to be relatively stable, rather than transient links that would come and go with the semesters.

• The technical implementation needed a low barrier to editing, to facilitate sustained student contributions.

With these principles in mind, it was clear that MIT OCW offered a wealth of resources from classes and departments across the MIT curriculum. The links include both Learn resources that explain Crosslinks topics (often those of foundational mathematics and physics classes) and Apply resources that demonstrate downstream applications (often those in engineering classes).

Engaging Students
The initial phase of the project resulted in a Confluence Wiki, with a page structure very much as shown in figure 1, and came online in the fall of 2011. Advertised by posters around campus and in classrooms, it attracted substantial student use but almost no student contributions.

We hypothesize two reasons for the lack of student input. First, and most obviously, the Wiki authoring module was very hard to use. But we think a second factor was in play: Students are very conscious of issues of standing. Were they really in a position to identify some word as a bona fide “topic” and to identify authoritative links connected with this topic? Apparently the student consensus was “no.”

Crosslinks has benefited from a fantastic team of undergraduate research assistants who have created, populated, and linked most of the collection.

We hired undergraduate students as research assistants to help populate the site. Throughout its six-year history, Crosslinks has benefited from a fantastic team of undergraduate research assistants2 who have created, populated, and linked most of the collection. Almost all of the entries have been done by hired staff; just a few entries but many more relationships among topics have been created spontaneously by students.

Reengineering to Enhance User Interface, Analytics
To address the concern about the Wiki authoring model, Crosslinks was reengineered to improve the user interface experience for students not only to access resources but also to contribute content. Huang joined the team in 2014 as technology lead for this effort, funded by a grant from the Lord Foundation. The site was restructured as a front-end (Web-based and mobile-responsive)

2 Danielle Hicks, Adarsh Jeewajee, Carmela Lao, Czarina Lao, Katherine Nazemi, Emma Nelson, and Jenny Sui.
application that fetches content data from representational state transfer (“RESTful”) Web application programming interfaces (APIs).³

Content data were restructured to be model-based, where topics and topic linkages are stored in a backend service created by the MIT Office of Digital Learning (ODL). This enables a much more scalable and simplified authoring experience: content is dynamically retrieved from the cloud and edits are saved back to the cloud. Users can easily select from topics, create linkages, and organize topics by subjects.

To discover user difficulties and reduce user interface friction, user experience research was conducted with students, faculty, and ODL content experts (MITx fellows). Iterative rounds of usability interviews, focus groups, and user testing led to the form and layout shown in figure 1.

In addition to marked improvement in student engagement and feedback, the technical restructuring enabled later implementation of clickstream analytics on individual topics and resulting insight on how students navigate and contribute to Crosslinks (further discussed below).

**OCW and Beyond**

As time went on, student Crosslinks editors pressed to include material other than OCW, especially in topics for which OCW material was lacking or deemed by the students to be less useful than other OERs. As a result, the Crosslinks collection now includes references to such resources. For example, Khan Academy videos provide a stable, high-quality set of links; and Wikipedia and Wolfram MathWorld, both heavily used by students, provide particularly useful links for brief topic definitions. Other outside references are included when suitable OCW resources don’t exist, the resource is accurate and of high quality, and there is reason to believe that the link is fairly stable.

Throughout its six-year history, Crosslinks has benefited immensely from collaborations with the MIT ODL Strategic Engineering Initiatives team: Jeff Merriman, Cole Shaw, and Peter Wilkins; and from discussions with Dipa Shah at the MIT Teaching and Learning Lab.

In an exciting new development, in March 2016 MIT OCW embedded links to Crosslinks for every OCW course page whose resources are linked under Crosslinks Learn and Apply. Users can now browse an OCW course page, navigate to Crosslinks to see the topics covered in that course, see the associated resource links, and navigate to the OERs. This integration⁴ demonstrates how Crosslinks can be used as a plug-in to an OER repository and enable navigation of the OERs. The Crosslinks codebase is open source and publicly available on Github,⁵ and we invite others to fork the repository to build a Crosslinks customized to their own institution.

**Crosslinks Use**

Crosslinks implements custom clickstream analytics on top of the Crosslinks topic network as well as individual resource links in the Learn and Apply sections to track how users interact with topics and resources. Individual clicks on topics and resources are logged for every visitor session, so that granular interactions can be analyzed on the learner level.

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³ A brief explanation is provided at https://en.wikipedia.org/wiki/Representational_state_transfer.

⁴ Carried out by OCW team members Joe Martis and Curtis Newton.

⁵ https://github.com/wombats-writing-code/crosslinks-js
Figure 3 shows a somewhat simplified typical student pathway through Crosslinks. The student first visits the **All Topics** page, then simultaneously opens tabs on **l'Hôpital’s Rule**, **Linear Approximation**, and **Quadratic Approximation**. The student accesses the MIT OCW resource on **l'Hôpital’s Rule** and spends 3 minutes there before clicking to **Indeterminate Forms**. There, the student spends 30 seconds before clicking to **Limit**, where the student accesses another MIT OCW resource and spends 4 minutes. The student finally clicks back to **l'Hôpital’s Rule** and accesses the MIT OCW resource, two YouTube videos, and a Khan Academy video (there were no more events registered after the Khan Academy visit and thus estimated time is unavailable for that resource).

These pathways recorded by the custom clickstream analytics enable fine-grained analysis of learner interaction with digital resources. For example, certain sequences of topics may be accessed more frequently than others. Or some resources may be more popular than others, but only when accessed in a particular sequence of topics.

These findings can help inform instructional designers and instructors who need to compose programs using OERs, and institutional administrators who need to survey and assess the landscape of their digital resources.

**Conclusion**

As open educational resources continue to proliferate online, structured ways to visualize and navigate them will become more important in order to facilitate and ensure their most effective use. Learners, instructional designers, and course authors need efficient access to resources.

Crosslinks provides a way to organize access to OERs, and is designed specifically to help students better appreciate the links between the various subjects they study at MIT. The design specifications allowed us to populate most of the site using student workers.

Our early vision was a resource “authored by MIT students for MIT students,” like Wikipedia relying on peer curation to expand and maintain accuracy. Whether Crosslinks reaches that state is still open to question. But in the meantime it is providing a valuable resource for our students.

**Reference**

Open educational resources (OERs) may be a solution to the high prices of instructional materials.

Open Educational Resources
Nearing an Inflection Point for Adoption?

Rebecca J. Griffiths and Nancy L. Maron

The rising cost of higher education and resulting financial burden on students and families have attracted increasing attention. One area of concern is the cost of course materials, which—at $200 for some textbooks—can be prohibitive for students. At the same time, more educational material is freely available online than ever before.

Awareness of financial stress and the growth of alternatives are generating interest in finding ways to make instructional materials more affordable. Open educational resources (OERs) have emerged as a potential solution to the high prices of instructional materials.

We review the current state of OER adoption and barriers to adoption, evidence supporting use of OERs, research challenges, and demand drivers. Our key takeaways are the following:

- Faculty demand for and adoption of OERs has lagged behind the enthusiasm of proponents, but the field may be approaching an inflection point that will lead to an acceleration in usage growth.

- Evidence of the potential benefits of OERs for students is encouraging, but there is a need for more rigorous study of both impacts on student learning...

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and economic impacts for students and institutions.

- Considerable uncertainty remains about the viability of OER provider models, especially given the changing market for instructional resources.
- Policies can encourage adoption of OERs and promote understanding of their potential benefits and long-term viability.

Development of Open Educational Resources

What Are OERs?
OERs are online teaching, learning, and research resources released under open licenses that permit their free use and repurposing. They encompass a wide range of materials, from a course syllabus to a professor’s PowerPoint slides, a video lecture, or an entire online course.

Advocates hope that educators will build courses around OERs in place of pricey publisher content, alleviating one component of the college affordability problem. But their aspirations go beyond making educational materials more accessible for students. Many seek to reshape the structures and value systems that underlie the creation and sharing of knowledge. The objective is to enable the “five Rs”: retention, reuse, revision, remixing, and redistribution of educational content (OpenContent.org/definition).

Many initiatives have been launched with public and philanthropic funding to create OERs, often led by faculty. Some projects aim to create original content, others to create tools and infrastructure to enable content contributions from volunteer authors. Finding the resources to sustain existing initiatives and launch new ones is a persistent challenge for the OER movement (Guthrie et al. 2008) as investors in educational technology put their resources into commercial (i.e., profit-yielding) rather than open access ventures.

Breadth of OER Content
OER efforts are not limited to the United States or college-level education. There have been extensive efforts internationally and in K–12 to advance OER development and adoption. We focus here on the OER landscape in US higher education.

Many OERs target foundational courses in science, technology, engineering, and mathematics (STEM), such as gateway math, biology, chemistry, psychology, and computer science. In these and other areas, OER alternatives to commercial textbooks are much sparser at advanced levels. A white paper released by the William and Flora Hewlett Foundation (2013, p. 9) observed that “[OERs do] not yet include a full set of high-quality materials for everyday use by educators in the most widely taught K–12 and postsecondary subjects.”

Impetus for Openness: Cost and Quality of Education

Costs of Textbooks
According to the US Government Accountability Office (US GAO 2013), from 2002 to 2012 the costs of textbooks rose 82 percent, compared to 89 percent for college tuition and fees and 28 percent for consumer prices (see figure 1). Thus on an annual basis, new textbook prices rose at nearly three times the rate of inflation. This continues a long-term trend: analysis by the American Enterprise Institute found that textbook costs increased over 800 percent from 1978 to 2012, well above general price inflation (Perry 2012).
What does this mean for students? The College Board advises full-time undergraduate students to budget roughly $1,200 per year to cover textbook costs, or a third of the total cost of tuition for a community college and 13 percent of the average cost for an in-state public four-year university.

It appears that students actually spend substantially less than these estimates, as free or lower-cost options for accessing materials have proliferated. There are robust markets for rentals and used textbooks, and a rapidly growing share of students—estimated at about 25 percent in 2014—report illicit acquisition behaviors such as sharing digital copies and downloading materials from pirated websites. One analysis found that, after accounting for all the options for accessing textbooks and other teaching materials, students spend on average $600–700 per year, still a hefty portion of their financial resources (Hill 2015).

There are disturbing trends underlying these data, aside from students resorting to illegal behavior. Several studies indicate that many students forgo the purchase of required textbooks because of cost.

- In a 2014 survey by Student Monitor, 31 percent of students reported that they did not purchase a required textbook because they could not afford the cost of a new book and another 12 percent said they could not afford the cost of a used book.¹
- The Student Public Interest Research Group (PIRG), an advocacy organization, argues that high textbook costs harm college completion and success rates, as students either do not enroll in the courses they need or refrain from buying assigned textbooks and hence fare poorly in their classes (Senack 2014).
- A 2012 survey found similar negative impacts on students (though the authors did not provide information about their sampling approach or response rates, making it difficult to gauge whether their findings were broadly representative) (Donaldson et al. 2012).
- Finally, the burden of high textbook costs is likely greatest for students who may already be academically at risk. An analysis of National Association of College Stores (NACS) data found that first-generation college students—who may be less familiar with alternatives for obtaining textbooks—pay on average 17 percent more per textbook than other students (Hill 2016).

Factors Behind Textbook Prices

Why haven’t prices for academic publications declined, given the increase in competition from online sources of content?

The factors driving rising prices are too complex to go into here in detail, but we draw attention to two important ones. The first is the absence of direct price competition for any given academic resource. A textbook is typically available only from a single publisher (i.e., there is rarely the equivalent of a generic drug). Furthermore, courses are often built around a specific textbook, so there is understandable reluctance to switch to a different textbook. And acceptable substitutes, if they exist, may be in short supply, particularly in more specialized courses.

The second (related) factor interfering with healthy price competition is that the people who choose instructional resources for courses (faculty) are not the ones who have to pay for them (students). With different incentives or priorities, faculty members might be willing to accept a slightly less well aligned or familiar resource available at a lower price.

Evidence for the second argument is mixed: in a 2014 national survey of faculty, less than 3 percent cited cost as a top criterion for selecting educational resources (Allen and Seaman 2014). Proven efficacy, quality, and coverage were by far the most important selection criteria. On the other hand, a survey by the Independent College Bookstore Association (ICBA) found that faculty cited cost to students as the second most important factor for selecting instructional materials (Green 2016). We thus cannot say definitively what role cost plays, but it seems plausible that faculty members are less sensitive to or aware of price increases and less likely to optimize value for money than they would be if they were paying for materials such as textbooks.

¹ The study is available at www.studentmonitor.com/f14/Fall14Deck.pdf.
Role of OERs

The OER movement aims to address the first of these factors by increasing the supply of viable substitutes that are freely accessible and cannot be used for commercial purposes. Efforts have focused on developing OER-oriented intellectual property policies, tools, and platforms, as well as original content—what movement leader David Wiley (2015) calls the “intellectual infrastructure of teaching and learning.”

In addition to low cost, advocates argue that OERs can improve the quality of instruction by prompting faculty members to rethink their pedagogical strategies and providing them with the flexible tools and resources to do so. As Lisa Petrides, founder of the Institute for the Study of Knowledge Management in Education, writes (Plotkin 2010, p. 1),

The real promise of [OERs] is not just the free high-quality learning materials and textbooks. It’s the process itself, how the materials are created, used, adapted, and improved, that creates a whole new set of possibilities.

The hope is that instructors will migrate from reliance on publishers’ materials toward dynamic communities of practice organized by, for, and with their peers.

A Snapshot of the OER Movement

In the late 1990s and early 2000s a number of OER initiatives were launched at universities with support from public agencies and private foundations, chief among these the William and Flora Hewlett Foundation. These efforts generated openly available course syllabi, textbooks, math education materials, and platforms for user-generated content. Recognizing the challenge of locating and vetting OER content, the National Science Foundation also funded development of curated pathways to open instructional content on the Web.

In the years since, countless domain-specific online resources have been created and deposited either with major platforms or on university and college websites and repositories. OER enthusiast communities have formed along with major gatherings such as the OpenEd annual conference. More recently, OER proponents have introduced services to support successful OER adoption by universities and colleges.

International efforts have also played a major role. In the United Kingdom, substantial investments from the Higher Education Funding Council and the Joint Information Systems Committee funded a program to support both open content creation and technical infrastructure. In 2005 the OCW Consortium was launched to provide an international forum and community, and in 2007 an international convening aimed at promoting OERs resulted in the Cape Town Open Education Declaration, which was signed by thousands of supporters.

State of Adoption

Yet for all the energy on the supply side of OERs, faculty have been rather slow to embrace these materials, especially as a primary instructional resource in place of commercial materials.

OERs can improve the quality of instruction by prompting faculty to rethink their pedagogical strategies and providing the flexible tools and resources to do so.

Lagging Adoption among Faculty

The 2014 national survey found that “between two-thirds and three-quarters of all faculty classified themselves as unaware of OER” (Allen and Seaman 2014, p. 2), although many faculty use OERs without being familiar with the term. Around 5 percent of faculty report regular use of OER material as their primary teaching resource, while just over 10 percent regularly use OERs for supplementary purposes (Allen and Seaman 2014, p. 37). Similarly, the ICBA survey found that 75 percent of faculty are either unaware of OERs or have never used or reviewed OER materials, but that 15 percent are actively using OERs in their courses (Green 2016).

In the K–12 sector, a 2013 review commissioned by the Hewlett Foundation found that only 10 percent of educators were using OERs as their primary teaching resource (BCG 2013).

This level of penetration seems consistent with the usage levels of major OER providers (e.g., MERLOT, NROC, Open Learning Initiative), whose users

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2 For a summary report of the main strands of this investment, see McGill et al. (2013).
3 Online at www.capetowndeclaration.org/read-the-declaration.
mostly number in the tens of thousands per month.\(^5\) OpenStax CNX, which provides open textbooks for large-enrollment gateway courses, reports that in 2015 its content was used by 392,000 students in more than 2,500 courses in the United States; it estimated that its free textbooks saved students $39 million.\(^6\) These are healthy numbers, though still fairly small in relation to the 20 million students enrolled in some form of higher education in the United States and the estimated $6+ billion college textbook market.\(^7\)

Perhaps in part due to slow uptake, central government funding for some major programs wound down: the National Science Digital Library (NSDL) transitioned to a private nonprofit and, in the United Kingdom, the national repository for open education content announced its impending “retirement” (Burke 2015).

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### The time and effort needed to locate, review, and incorporate OER materials are the largest obstacles to OER adoption.

**Barriers to Adoption**

What has held back uptake of OERs? The simplest explanation may be that they are not (yet) particularly well aligned with faculty priorities. According to the 2014 faculty survey, trusted quality, proven effectiveness, and coverage are the three most important factors, and ease of use also ranks quite high. Ease of adaptation and reduced cost—particular advantages of OERs—are lower priorities. In fact, a 2012 study found that over 90 percent of instructors who use OERs simply adopt them “as is” without adaptation (Hilton et al. 2012).

### Time and Effort to Find and Assess Materials

When faculty are asked to cite the largest obstacles to OER adoption, time and effort are at the top of the list (Allen and Seaman 2014). Specifically, in the absence of a catalogue of available materials, efforts to locate, review, and incorporate OER materials into a course are a major undertaking. For those who carry heavy teaching course loads, receive last-minute teaching assignments, or are obliged to teach courses outside their core area of expertise, assembling a course using OERs could appear formidable. Without institutional policies providing release time from teaching and needed technical support for faculty, instructors bear the costs of transitioning to OERs, while it is primarily students who reap the benefits.

### Copyright, Compatibility, and Coverage

Other factors may discourage faculty from using OERs. Confusion over copyright policies may deter instructors from adapting materials. Compatibility of online and offline resources and seamless integration with campus learning and authentication systems are also important needs, which OER providers may not be equipped to address. Finally, instructors want topic coverage, and commercial publishers have a very long head start in building comprehensive libraries of content.

### Need for Evidence of Effectiveness

We frequently hear from faculty and administrators that evidence of effectiveness is a key factor for adoption. This is curious given that many widely used publishers’ materials, particularly online ones, are not supported by rigorous quantitative research showing that students who use them perform better. Case studies and correlational analyses that fall short of causal evidence are far more common.

It may be that faculty members have more confidence in publishers’ resources based on accumulated experience and comfort in numbers (“how could thousands of instructors be wrong?”). It is also likely that decisions are influenced by commercial publishers’ advertising and marketing efforts, which OER providers are unable to match.

Because the transition to OERs requires a substantial commitment of time and effort, it is understandable that instructors set a high bar for evidence. It is also appropriate for administrators and legislators to seek solid

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\(^4\) The Open Learning Initiative (oli.cmu.edu) was a pioneer in developing interactive online courses.

\(^5\) Based on estimates from similarweb.com and compete.com, services for tracking web traffic.

\(^6\) Information posted at http://us2.campaign-archive2.com/?u=93c7b211839bc41ae96700913&id=d630a25c82&e=c1d147940, accessed June 15, 2016.

\(^7\) Reliable data on the size of the textbook industry are not readily available. McKinsey & Company estimated the market for college course materials at $10 billion, of which $6 billion is deemed “addressable” for textbook publishers (Benson-Armer et al. 2014). A 2014 *Wall Street Journal* article estimated the college textbook market at $7 billion (Mitchell 2014).
Evidence on which to base OER-oriented policy changes. Does this evidence exist?

**Evidence Base for OERs**

Rigorous research on the academic and economic impacts associated with OERs is still fairly limited. We also believe that the harm to students from high textbook costs, while intuitively compelling, merits greater scrutiny.

A review conducted by SRI in summer 2015 on behalf of the Hewlett Foundation found that “the majority of research on OER can be characterized as exploration, description, or advocacy rather than controlled empirical tests of efficacy” (Shear et al. 2015, p. 3). This finding was based on a review of studies published in 2012–2014 in a prominent journal in the OER field and on interviews with experts in OERs and OER research and other stakeholders (figure 2). SRI’s review of 78 articles found only two that qualify as impact studies (experiments or quasi-experiments comparing outcomes of students in courses using OERs with courses using traditional publisher content).

**Student Outcomes**

A recent review of nine efficacy studies of OERs (two of them set in secondary schools) found that many of the studies had methodological limitations—for example, they compared courses that use OERs with different courses that do not, used historical comparison groups without controlling for student characteristics, or lacked tests for statistical significance (Hilton 2016).

Notwithstanding these limitations, the evidence is mostly encouraging. Of the nine impact studies, four found improvements in student outcomes on at least one dimension, while the other five found no difference in outcomes. Only one study found possible evidence of harm, as students in OER sections performed worse in two out of seven courses examined (business and psychology) (Hilton 2016). A recent multi-institutional study involving over 16,000 students found that those whose instructors chose OERs performed as well as or better on key outcome measures in 14 of 15 courses examined (Fischer et al. 2015).

Surveys also find consistently positive perceptions among students based on their experiences with OERs. For example, in a study of participants in Project Kaleidoscope (an initiative to promote OER use in eight community colleges), 97 percent of students surveyed responded that OER texts were about the same or better in quality compared to other texts (Bliss et al. 2013).

Hilton (2016, p. 16) observed a general pattern in survey findings that “roughly half of students found OER to be comparable to traditional resources, a sizable minority believed they were superior, and a smaller minority found them to be inferior.” Again, some of these studies have methodological flaws, but the preponderance of evidence seems to point in a positive direction for OERs.

**Costs**

Many OER-related studies report substantial cost savings to students, usually by multiplying the number of students involved by what they would have paid for textbooks. But these calculations have two common flaws. First, they use the price of a new textbook to calculate savings, whereas only a fraction of students actually pay this price. Second, the studies often account for only part of the picture: although OERs are free to students and undoubtedly do save them money, evidence suggests

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8 A number of these studies are available at the Open Education Research Hub (http://oerhub.net).
that incorporating them in courses involves significant costs to institutions and/or faculty. A study by David Wiley and colleagues (2012) found that the adoption of OERs in high school science courses increased cost per student in the first year (costs declined the next year).

A useful analogy is open source software. There has been a longstanding debate as to whether it saves money for users when taking into account the total cost of ownership (the staff time involved in installing, customizing, and maintaining the software, training users, and so forth). As Kenneth Green of the Campus Computing Project famously wrote, “Open source is not a free beer, it’s a free puppy” (Bubinas 2014).

One must also consider potential printing costs for OER materials, as some students and instructors prefer not to consume instructional materials online. Discovery and vetting of OER materials also takes time, though we have not seen data on how this process compares to that of commercial materials.

**Discovery and vetting of OERs takes time and incorporating them in courses involves significant costs to institutions and/or faculty.**

In short, OER use may involve a transfer of costs from students to institutions and/or faculty. This possibility in turn raises the question of whether OER adoption is the best use of institutional resources, or greater gains in student outcomes might be achieved through alternate use of those resources (say, better advising). We are not arguing that this is the case, but that these are important questions that warrant attention.

**Research Challenges**

Research to test the effects on student outcomes of a particular set of educational materials is expensive, time consuming, and difficult to execute. Consequently, large-scale, randomized trials for any types of online learning resources are still rare.

The OER field faces particular challenges, starting with the fact that OERs encompass a broad variety of educational resources. Empirical studies have mostly focused on OER textbooks, leaving much of the other content unexamined.

The impact of supplementary uses of OERs (e.g., a slide deck or a learning activity) is hard to measure, and small-scale tests of specific resources have limited generalizability. Moreover, OERs do not generate revenue streams from users that can be used to fund expensive research.

Another challenge stems from a situation many professors will recognize: any time a course is redesigned with new instructional materials it is likely to cover different content, complicating comparisons of student outcomes with traditional versions of the course. This is especially true with OERs, which are intended to prompt changes in pedagogy and may also be heavily customized for any particular implementation. Thus, studies of OERs are likely to compare versions of courses that differ on more dimensions than just the instructional materials. They may be able to measure impact on higher-level outcomes (e.g., course completion and pass rates), but performance on more precise measures of learning (e.g., final exams) may not be meaningful. Extensive customizations may also make it difficult to replicate a particular study.

An additional concern is the potential blurring between research and advocacy, as many studies have been conducted by strong proponents of OERs. This is not surprising, given that champions are most motivated to undertake such studies. It is possible, however, that this research is less convincing to faculty who are hesitant to embrace OERs.

For example, one study conducted by an agenda-driven organization is often used to make the case for OER-favorable policies. A PIRG survey finding that 65 percent of students do not buy required resources is pervasively cited in OER literature, sometimes as the only evidence supporting the claim that students are harmed by textbook costs (Senack 2014, p. 11). But the PIRG report does not make any pretense of objectivity, and the organization itself promises to conduct “hard-hitting research” in support of lower textbook costs. It acknowledges that students have many more options than purchasing new textbooks but does not report on what percentage of students pursue those options (although this question was included in the survey).

In a survey by the more neutral Student Monitor, students report *acquiring* 91 percent of required textbooks (4.3 out of 4.7 per term), and 70 percent of students report *purchasing* all of their required textbooks.9 Of those that do not purchase required textbooks, fewer than half reported that affordability was the reason (22 percent.
responded that they did not purchase a book because the professor does not use it) (also see, e.g., THECB 2014).

Of course one would hope that all students have unfettered access to required instructional materials. Our point is that the question of how the costs of educational resources impact students is serious and complex and deserves more extensive scrutiny.

In sum, there is clearly a need for high-quality research on the effectiveness and cost impacts of OERs, ideally conducted by neutral observers who are not involved in implementation. Few if any of the impact studies available on OERs would be accepted by the Department of Education’s What Works Clearinghouse (http://ies.ed.gov/ncee/wwc), which aims to set a high standard for education research (the same could be said for evidence supporting claims by commercial publishers). We know of some studies in progress and look forward to deeper examination of research questions associated with OERs.

Progress toward an Inflection Point

Three important trends may shape the future of OERs, and each raises important questions:

• increasing alignment of demand drivers,
• evolution toward open education, and
• emergence of adaptive learning technologies.

Demand Drivers

A number of developments seem to be aligning that may kick OER adoption into a higher gear.

Approaching Scale

Diffusion theory suggests that innovations reach a tipping point once they penetrate 15–20 percent of a market and make the jump from “early adopters” to the “early majority” (Rogers 2003).

Use of OERs as a primary instructional resource has a ways to go, but their regular and occasional use for this purpose is reported by 17.3 percent of faculty (Allen and Seaman 2014, p. 37), and about 35 percent of faculty say they use OERs as supplementary resources at least some of the time. Given that those with experience using OERs tend to report positive experiences, it is reasonable to expect that growing familiarity will lead to greater adoption.

The latest push to scale up OER adoption is through creation of entire degree programs using all open instructional materials. This model was pioneered at Tidewater Community College and will soon be implemented at 38 colleges across the United States through a multifunder initiative led by Achieving the Dream.10

There is clearly a need for high-quality research, conducted by neutral observers, on the effectiveness and cost impacts of OERs.

Legal Infrastructure, Policies, and Administrative Support

Substantial progress has been made in establishing a legal infrastructure that supports the creation, sharing, reuse, repurposing, and resharing of open educational content. After a few false starts, Creative Commons licenses have become widely used and accepted.

Public policies promoting OERs have proliferated.11 In 2014 the White House announced several initiatives to support open content (Garg and Chien 2014), and the Department of Education recently appointed its first OER advisor to lead “a national effort to expand schools’ access to high-quality, openly licensed learning resources” (US DoED 2015).

In addition, some state legislatures have set up open textbook collaboratives, and others specifically encourage the use of OERs (Bakia et al. 2015).12 California, for example, provides incentives for community college faculty to redesign courses using OERs.

In K–12, policy levers can play a powerful role in driving adoption given relatively centralized authority over procurement and curriculum. In higher education, policymakers and administrators can provide credibility and other forms of support for OERs, but they have limited  

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9 Converting Data to Insight, fall 2014, p. 67. Available at www.studentmonitor.com/f14/Fall14Deck.pdf. The Student Monitor provides syndicated and custom market research services.

10 For more information see http://achievingthedream.org/resources/initiatives/open-educational-resources-oer-degree-initiative. SRI is the research and evaluation partner for this initiative and I (Griffiths) am the project director.

11 Advocates of open access to research have been similarly successful in bringing about policies that require certain federally funded research to be publicly available within a short period of time.
ability to prescribe what resources are used in the classroom. Individual faculty members typically make decisions about what instructional resources they will use in their classes. Use of OERs probably makes the most sense when implemented across an entire course or program given the time and effort involved to review and incorporate the materials, but in many postsecondary contexts this level of coordination is not the norm. Does widespread adoption of OERs require more centralized decision making about selection of educational resources?

Greater institutional support is a crucial ingredient given the time and skills needed to find and use OERs.

Greater institutional support is certainly a crucial ingredient given the time and skills needed. In 2010 Hal Plotkin, author of *Free to Learn*, wrote: “Higher education governance officials need only summon the will and enact governing board policies that institutionalize support for [OERs] to move these activities from the periphery of higher education to its core, where the results would be truly transformative” (Vollmer 2010). This seems like a clear call for an increased administrative and/or policy role in promoting this class of instructional materials and approach to course design.

We have seen many cases in which OER use starts with an individual professor, who then evangelizes OERs among colleagues and administrators. This has probably been the prevalent scenario over the past decade, but it is not often an effective approach for rapid uptake. It seems likely that top-down support and bottom-up interest are both necessary for adoption. The question is what combination of these two forces can lead to widespread change in a reasonable time frame.

Evolution toward Open Education

OERs are part of a broader vision for “open education,” which the Open Education Consortium (www.oecconsortium.org) defines as encompassing “resources, tools, and practices that employ a framework of open sharing to improve educational access and effectiveness worldwide.”

There may be tension between the two core tenets of open education: free and open. Some leaders of the OER movement adamantly oppose any relaxation of the “open” requirement (Wiley 2015). But it seems inevitable that as OER use continues to spread, new constituents will have different needs, perspectives, and priorities.

For example, massive open online courses (MOOCs), hosted on platforms like Coursera and edX, are mostly free to users but carry very restrictive license terms (Griffiths et al. 2015). On the other hand, they offer users something most OERs do not: a semblance of participation in a course taught by a professor, complete with assessments and a community of fellow students. In that sense even proprietary MOOCs arguably do more to make instruction widely accessible than OERs, which mostly provide content but not an educational experience.

MOOCs are just one example of educational services on the Web that fall somewhere between open and restricted. Given that business models for MOOCs, OERs, and for that matter much Web-based content are still emerging, it is possible that goals of open education might be met by services without fully open models. Should the OER movement pursue a “big tent” approach embracing participants with both shared and divergent interests?

Emerging Technologies

The president of McGraw-Hill, a major publisher, recently stated that “Textbooks are dead. They are dinosaurs” (Smith 2014). The online elements once considered “ancillaries” are now replacing printed texts as the principal revenue drivers and focus of investment. Major publishers are building next-generation capabilities—such as adaptivity and continuous sharing of student progress with professors—into their digital products.

At the same time, investors are pouring millions and even billions of dollars into commercial ventures in education technology. Ambient Insights reports edtech investment in the United States of $3.2 billion in 2015, of which $658 million went to ventures serving higher education (Adkins 2016). Even if only a fraction goes toward new product development, these resources dwarf the funding available to support OER development.

What does this mean for OERs? There is debate in the community about whether to focus on developing open alternatives to gateway course textbooks (Wiley’s “content infrastructure”), given that so many instructors still rely on textbooks, or on the development of next-generation learning technologies. An important question is how OERs can compete in this space, which could well
favor resource-rich enterprises operating at large scale, as has been the case for most Web-based services.

Universities have access to computer science, learning science, instructional design, and domain expertise, so they are well positioned to lead in new technology R&D. In fact, some of the most important edtech developments originate in university centers and labs, but their record of scaling up use of such technologies is mixed and tends to involve spinning them off into commercial ventures (e.g., CMU’s sale of Carnegie Learning to the University of Phoenix’s parent company).

There are few enthusiasts in the higher education community for a future in which a handful of companies dominate the market for advanced learning software and reap the benefits of scale, such as ownership of massive quantities of student learning data. But this feels like a real danger when market forces on the Web have tended toward winner-take-all outcomes—as illustrated by Google, Amazon, Facebook, and Uber.

Concluding Thoughts

One can imagine an alternative future characterized by a robust ecosystem of OER communities of practice, perhaps coexisting with boutique commercial applications. Such a scenario would require concerted efforts by administrators to provide support and free up faculty time and attention. It would probably also require a change in culture, whereby faculty embrace a role as curators of instructional resources—and are more willing to relinquish ownership and control of their intellectual creations (as happened with MIT’s launch of OCW; see Miyagawa in this issue).

In any case, the future of OERs may not be up to institutions or faculty to determine. Students are the ultimate consumers of educational resources and are beginning to exercise more choice over how, when, and where they pursue postsecondary education. Any organization, publisher, or developer aiming to provide educational resources, open or not, will need to provide engaging, effective, and, ideally, inspiring experiences for students.

References


Recovery of Rare Earths from Coal and Byproducts
A Paradigm Shift for Coal Research

Coal is an important resource, both in the United States and around the world. The United States generates approximately 30 percent of its electricity through coal combustion and, at the current overall rate of consumption, has more than a 250-year supply of coal.

According to the US Energy Information Administration’s July 2016 Monthly Energy Review, approximately 1 Gt of coal has been mined annually in the United States over the past 25 years, although the 2015 total was 896 million tons and 2016 is projected to be less than 700 million tons. The recent decline in domestic coal production is due to the availability of inexpensive natural gas, regulatory uncertainty with regards to carbon dioxide emissions, and the retirement of older coal-fired power plants.

In the United States most coal is burned for power generation, but substantial quantities are also used in the manufacture of steel, chemicals, and activated carbons. Numerous industries—such as mining, power, rail transportation, manufacturing, chemical, steel, activated carbon, and fuels—are involved in the production, transportation, and use of coal.

Rare earth elements (REEs), which comprise the 15 lanthanide elements as well as scandium and yttrium, are present in the abundant coal and coal byproducts produced domestically and worldwide. Widely used in high-technology products such as catalysts, cell phones, hard drives, hybrid engines, lasers, fluorescent lamps, batteries, magnets, medical devices, and televisions, REEs are of significant value to US national security, energy independence, economic growth, and the country’s environmental future.

Everything that is in the Earth’s crust is also present in coal to some extent, and the challenge is to use coal in clean and environmentally friendly ways. Most of the common inorganic lanthanide compounds, such as the phosphates found in coal, have very high melting, boiling, and thermal decomposition temperatures, allowing them to concentrate in combustion and gasification byproducts.

Rare earths are commercially produced from ores containing monazite (rare earth phosphate mineral) or bastnäsite (rare earth carbonate-fluoride mineral) as well as from ion exchangeable clays. They are also found in coal; combustion byproducts such as ash, coal preparation residues, gasification slags, and mining byproducts; and the strata above and below some coal seams, thereby making every process in the mining and utilization of coal a potential source of rare earth elements.

Of further interest, some coal and coal byproducts have elevated concentrations of heavy rare earths (HREEs). These are lowest in supply, rank high in criticality and price, and are projected to increase in demand,
making them potentially attractive targets for REE recovery despite their overall lower concentration.

The National Energy Technology Laboratory (NETL) Rare Earth EDX Database (https://edx.netl.doe.gov/ree/) is a resource for rare earth information related to coal and byproducts. The NETL Research and Innovation Center (NETL-RIC) recently initiated research to support the measurement of concentration, identification of rare earth compounds, and recovery of rare earths from abundant domestic coal byproducts. Many other research organizations have also initiated efforts for the analytical characterization and recovery of rare earths from unconventional sources such as coal byproducts.

Much of the recent research on coal use in the United States has focused on the capture of pollutants such as acid gases, particulates, mercury, and carbon dioxide. The possible recovery of rare earth and other critical elements from abundant coal and byproducts is an exciting new research area and represents a dramatic paradigm shift for coal.

The development of an economically competitive domestic supply of REEs will help to maintain the nation’s economic growth and national security. But additional research and data are needed on the rare earth contents of coals and byproducts in order to determine the most promising feed materials and extraction processes. Future work will focus on characterization of coals and byproducts and on separation methods for the recovery of rare earth elements.
An Interview with . . .

Dennis Kelly

Ron Latanision (RML): Cameron and I are so pleased to talk with you. We have observed that engineers often do things that go beyond their engineering education—for example, there are engineers who have been president of the United States, members of Congress, poets and authors, astronauts….

Dennis Kelly (MR. KELLY): Who, besides Washington, do you count as an engineer that was president?

RML: Jimmy Carter had a background in nuclear engineering, and, Cameron, didn’t Herbert Hoover also have an engineering background?

Cameron Fletcher (CHF): Yes, he was a mining engineer.

RML: Those are the two that come immediately to mind.

MR. KELLY: Washington was a surveyor, so I give him an honorary civil degree.

RML: Fair enough, I accept that. In any case, we wanted to illustrate to our members and readers that engineers affect the culture of the country in many ways. It occurred to us that you are a prime example. The $64 question is, How did you, as a mechanical engineer, become director of the National Zoo? Maybe we should begin with your history.

MR. KELLY: Sure. I grew up and went to high school in Atlanta. When I graduated I started as a physics major at Georgia State University. The Vietnam War was winding down but I thought I was going to be drafted so I went ahead and volunteered and served two years in the Army. When I came back I decided to switch to Georgia Tech, and instead of physics I went into mechanical engineering. I loved it.

I have a couple of anecdotes from my experience there. When I graduated—we were still in the quarter system at Georgia Tech—I did a rough count and about half of the people graduating with me that quarter, ending in December ’76, were veterans. The old GI Bill was still in effect.

For the other anecdote, I don’t remember what my GPA was but I think it was 3.2, maybe 3.3—not a sterling GPA by today’s standards. I got notice from my advisor that I was going to graduate with honors. I said, “That is impossible—I have a 3.2 or 3.3.” He said, “No, that is the top 15 percent of the class.” I always thought that was interesting in today’s era of grade inflation.

From there I went to work. I had a number of offers and I went to work for Procter & Gamble in their engineering division on the food side—Pringles, shortening and oils, Duncan Hines.

CHF: What were you doing for the food side of the company?

MR. KELLY: They were starting up a new plant in Jackson, Tennessee, and trying new management techniques. While my family lived in Jackson, I was actually part of the engineering department of Cincinnati. We had a couple of engineers there that were trying to start these plants with brand new technologies. So it was a Pringles plant and then we built a Duncan Hines plant. As I was leaving they were building a shortening and oil plant. They had onsite nitrogen generation and steam generation. They had the capability to generate electricity but didn’t.

It was a lot of fun as a young engineer to work in applied engineering in a food plant startup.
CHF: I would not have associated mechanical engineering with food.

MR. KELLY: Oh my goodness, between packaging and processing, there is a lot of technology in food manufacturing.

RML: How long were you with P&G?

MR. KELLY: Just shy of 4 years. I applied to and was accepted into the Harvard Business School, a little bit to my surprise. The engineering curriculum is so intense that I was quickly drafted into management and I was managing the boiler house, all the utilities operations—nitrogen generation, compressed air, steam—and I was suddenly manager of a four-shift operation. I remember going to my boss and saying, “We need a new compressor and I think we will save money.” He says, “Great, just do the ROI and the IRR and submit it and we’ll take a look at it.” I said, “Can you spell ROI and IRR for me?” I realized I needed some more training! That’s when I decided to apply to business school and was fortunate enough to be accepted to Harvard. That changed the direction of my career into both finance and marketing. It rounded me out.

In hindsight, I would do everything the same. I think the mechanical engineering degree prepared me very well for what I’m doing.

While I was at Harvard I spent much of my second year not at the Business School but at the Kennedy School of Government studying energy and environmental policy.

RML: I notice you have some experience at Green Mountain Energy Company.

MR. KELLY: That’s right. From Harvard we wanted to come back south, so after a brief stint in consulting I went to work for the Coca-Cola Company and got into the general management track. I did finance, general management, and marketing. In my last job at the company, after 16 years, I was deputy chief marketing officer and director for Europe.

From there I got recruited to run a startup called Green Mountain Energy, a spin-off of the utility company in Vermont. It was marketing clean electricity—wind and solar. We were selling electricity into deregulated markets, but it was 15 percent more expensive to buy the energy tax credit for electricity made from wind and solar and combined cycle and natural gas.

When I took over, Green Mountain was hemorrhaging cash, so I quickly needed to raise a lot of money—about $100 million—to get the company cash flow positive. We did and in the process brought in more investors—BP and a Dutch electric company—and moved the company from Vermont to Austin, Texas. It has since been sold, but the brand is alive and well today.

After I moved the company, my family wanted to stay in Atlanta. I had been commuting the whole time, so I was looking for something to do when a headhunter called and said had I ever thought about running a zoo? I said no. But they said the situation was similar—a turnaround with a terrific mission.

The mission of Zoo Atlanta is to save species from extinction. At the time the zoo needed a full general management makeover that included capital investment and fund raising and financial management. While I was there I took it from an operating deficit and an operating debt to being debt free and cash-flow positive. That was very, very satisfying for me, and also because I got to work with scientists and folks who are passionately involved in a mission to save species from extinction.

RML: It’s pretty clear that with your particular skills you were the right guy at the right time for those organizations. That is a great testimonial.

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I think one of the things that attracts folks with engineering backgrounds is the capital intensity of organizations.

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MR. KELLY: I think one of the things that attracts folks with engineering backgrounds is the capital intensity of organizations. Zoos, by their very nature, are capital-intensive organizations, and management of that capital, both physical and human, is a challenge for somebody who has not received the kind of disciplinary training that you get in engineering school.

RML: I have to admit, Dennis, I was expecting you to say, ‘Well, I grew up on a farm and I really liked animals and this was an opportunity I just couldn’t pass up.’ But that is not the case.

[Laughter]
Mr. Kelly: I think the emotional draw for me is that, from my very early days in training, I've been interested in the intersection of environment and environmental policy. When I was in graduate school I was fortunate enough to intern at the Harvard Energy and Environmental Policy Center.

The other thing I learned early on is that as you begin to make your career choices, you will be happiest if you are working around people that you like working with.

It turns out that I like working with scientists, engineers, and people with deep training on the science side. And my own skills are in optimizing organizations, particularly those in transition.

The Conservation Biology Institute is where we study and breed and understand the sustainability of critically endangered species.

RML: That’s a very interesting history. On a personal note, I grew up in the coal mines of Northeast Pennsylvania. In my living room in Massachusetts I have a chunk of anthracite coal. I keep it as a reminder of my youth, I guess. I’m very concerned about the environment, about global warming and related issues. It seems like something of an anachronism to have this chunk of anthracite coal in my living room. But I do point out to people that it is bituminous coal that is usually used in electric generation, so I feel a little bit reprieved.

Mr. Kelly: I bet if you look microscopically you will see some ferns or early flora buried in there. You have stored solar energy on your desk.

RML: Absolutely. I used to enjoy that when I was a kid—our playgrounds were deserted coal mines. When I was growing up the coal industry was on the decline in Northeast Pennsylvania, and we used to find our way into mine shafts. It was very interesting to look at the morphology of the coal being pulled out.

Tell us a little more about the National Zoo. I know it involves not only a facility for the public but also a Conservation Biology Institute, which is much larger in terms of physical plant—

Mr. Kelly: Yes, the Smithsonian Conservation Biology Institute is 3,200 acres, as opposed to the 163 acres at the zoo in Rock Creek Park in Northwest Washington. There are a lot of buildings on that campus, although in terms of both the number of people and the size of the collection it's smaller. It's a 100-year-old facility—an old military post originally intended to breed and train horses for cavalry battles—that we took over in 1976, recognizing the need for an offsite research and breeding program. It's a gorgeous facility at the top of the Shenandoah Mountains in Shenandoah National Park where we study and breed and understand the sustainability of critically endangered species.

We have also built an undergraduate and graduate training facility for training the next generation. It's a LEED gold-certified facility that we built in conjunction with George Mason University (GMU), part of the Virginia university system.

RML: There are students onsite?

Mr. Kelly: Yes, they do classwork in the morning and field work in the afternoon, with animals and the ecosystem. They work toward their degree in biology or zoology or public policy in terms of biodiversity.

CHF: What interaction do you have with those or other students?

Mr. Kelly: I'm out there once or twice a month. I'm not teaching but am on the executive committee that jointly runs the facility with GMU. It's a very exciting program.

In addition to two undergraduate cohorts every semester, we teach about 15 graduate courses in a two-year rotation cycle. They tend to more intensive, 1- and 2-week courses on everything from GIS and tracking of animals and migration, to microbiology to maximize genetic diversity in small populations of animals, things like that.

RML: Is this available to students beyond George Mason?

Mr. Kelly: Only about half the students are GMU students; the rest are from around the world.

CHF: About how many students are there?

Mr. Kelly: In the fall semester we have almost 40 undergraduates and in the spring 20 to 30. At the graduate level, we have hundreds of students a year taking short courses there and around the world.
CHF: “Around the world”?

MR. KELLY: Sometimes we teach courses in other parts of the world, such as China or Southeast Asia. Details are on the Smithsonian-Mason School of Conservation website (http://smconservation.gmu.edu).

RML: I am also reading about Speedwell. What is the Conservation Carousel?

MR. KELLY: A childhood friend of mine, Mike Messner, is a fellow Georgia Tech grad (he got his degree in civil engineering) who became a hedge fund manager in New York. We were talking and he said he had done well and wanted to help the Smithsonian zoo. I invited him to fund the Conservation Carousel. It was attractive to him because it was an opportunity to both better engage people with our conservation mission and generate revenue for it. The carousel has a net positive cash flow of about a half million dollars a year. Think of it as the equivalent of a $10 million endowment that is adding to the fun and conservation mission of the zoo.

The carousel is 58 American-made hand-carved figures made of sustainable basswood. Every animal is unique to our collection.

As the donor, Mike wanted only two things on the carousel. He didn’t want his own family name on it, he wanted his family foundation name on it: Speedwell. But he asked for two characters. His wife is an equestrian, so he asked for a regular horse—it’s carved in the likeness of her favorite horse. The other is another species that is not endangered, the Georgia Tech yellow jacket.

Two other Georgia Tech graduates, engineers, are involved. One is the former president, John Huffman, of Pepco Energy Services, a local utility that provided the solar panels that power the carousel. And at the time the secretary of the Smithsonian was another Georgia Tech alum, Wayne Clough (NAE), who got his bachelor’s and master’s in civil engineering. We were all there for the dedication, so the first song played on the carousel the first time it went around was the Georgia Tech fight song.

RML: I feel loud applause from the crew. That’s cool.

CHF: So, other than the two you mentioned, they are all endangered species represented on the carousel?

MR. KELLY: Yes.

CHF: What are some of those species?

MR. KELLY: Giant pandas, gorillas, Asian elephant, coral. And every one of the critters has a sponsor. My wife and sons sponsored the sloth bear, which is native to India.

CHF: I hate to ask this, but is there room to accommodate more species in danger of extinction?

MR. KELLY: I wish. No.

RML: Dennis, I would like to turn to another issue for a moment. You mentioned that your educational pathway included the GI Bill. It was a very important piece of legislation in this country many years ago. I know there was a post-9/11 version of the GI Bill. Do you have any thoughts on how effective the current version is in terms of providing support for our returning veterans?

MR. KELLY: I do not. I wish I did. Everything I’ve read about the GI Bill that I was fortunate enough to use is that it had a massive positive effect on our nation. And by my own estimate, half the people who graduated with
me at Georgia Tech were there because of the GI Bill. Many of us would not have been there without it. I was able to complete Georgia Tech in three years and then apply one year of GI Bill funding to Harvard.

RML: I ask because I have been reading in the press some accounts of what appear to be predatory practices on the part of for-profit universities and colleges. It seems that veterans have been targeted by some of those organizations.

We are in the midst of the sixth great extinction crisis. The last one was 65 million years ago.

CHF: On a different topic, I wonder whether you might be willing to comment on what happened at the Cincinnati Zoo.¹

MR. KELLY: Sure. First, in full disclosure, I am going to be the chair of the Association of Zoos and Aquariums (AZA), which is the premier accrediting organization in the world for zoos and aquariums.

CHF: Congratulations.

MR. KELLY: It is one of those things that, like your own profession, sometimes as you rise up in the profession it is a mixed blessing. This year it is particularly interesting because every ten years or so the association replaces the executive director due to retirement, so we are recruiting a new executive director. It is both exciting and challenging.

The association has a 40-person staff in Silver Spring, Maryland, that accredits zoos and aquariums, mostly in North America but also in other countries, with what is considered the highest standard of accreditation for aquariums and zoos in the world.

Regarding the Cincinnati tragedy, there are two things I would say. First, I absolutely agree, based on everything I know at this point, with the decision that the director there made. I know that director, and I know the staff. You never really know when you are not there, but in similar circumstances I would have done the same thing. Human life and safety are always our first priority.

The second thing I would say—and this goes to engineering—is that the challenge when we are keeping animals in human care is the safety interface between humans and animals. We are always improving. At my own institution, going back almost four years now, we have been taking exhibits that were unchanged for 30 years and adding safety and security measures to them such that, whether accidentally or by intention, it is very difficult for a human or an animal to be injured. We have reengineered five or six major exhibits that never had an incident for decades, but in an abundance of caution we are reengineering them.

But I want to make sure that people know the main reason that I and the 30,000 people who work in the 233 accredited zoos and aquariums come to work every day is because the animals we care for are in the midst of the sixth great extinction crisis.

According to Harvard biologist E.O. Wilson, we are losing animals at a thousand times the background rate. It is being called the sixth extinction event of our planet. The last one was 65 million years ago. This one is approaching the same order of magnitude.

CHF: What are the causes of that extreme rise in extinction rate?

MR. KELLY: Humans. We have only set aside and formally reserved about 15 percent of the planet—sometimes the least desirable parts of it—to be completely wild. Another 30–35 percent is semi-wild. The 7.5 billion people on the planet are crowding out the rest of the species and terraforming the planet.

Some of my colleagues at the Smithsonian think that, a couple of hundred years ago, we entered a new epoch, called the Anthropocene period. One species has completely changed forever the sustainability, the nature of our planet.

My colleagues and I are doing our best to help humans not kill off species at the rate we have been killing them off. Think about the passenger pigeon, the Carolina parakeet—all kinds of species that we have been killing off. We are trying to reverse that.

RML: What is it that humans are doing that affects their longevity?

¹ On May 28 a 17-year-old western lowland gorilla named Harambe was killed by zoo staff to protect a 4-year-old boy who had slipped through a barrier and fallen into a moat in the gorilla compound.
MR. KELLY: Usually it is loss of habitat. Sometimes it is direct intervention. For example, in the 1800s the US government, as a matter of public policy, wanted to control the Native Americans. One of the military strategies was to deplete their food source, the bison. At the turn of the 19th century we had already depleted what we think was a 30-million-head herd of bison down to a few thousand. As a strategy to contain native peoples we proceeded to systematically try to wipe out the rest of the bison.

The Smithsonian actually was involved with recognizing and understanding that in 1888 there were probably less than a thousand North American bison left in the world. They shipped a couple of bison to Washington, and they were the first two animals in the National Zoo.

We are now back up to half a million bison, but many of them have been cross-bred with cattle.

RML: Does climate change play a role in affecting the habitat of the animals you are concerned with?

MR. KELLY: Absolutely. We don't know what all the impacts of climate change are going to be. But I will give you one example. Here at your National Zoo one of the things we do very well is understand animal disease. As you know, 70 percent of human diseases come from animals—measles, mumps, rubella, Ebola, smallpox, avian influenza. All these are diseases that start in one species and jump to another.

We discovered a disease in frogs called the Chytrid fungus that interferes with respiration through the skin of the frogs. It's being spread by climate warming and has wiped out, for example, a third of all the frog species in Central America—they're just gone. Once we discovered this disease we took a lot of species into human care because in a zoo we can protect them from the fungus. We can clean them up, keep their environment safe, and they thrive. But we cannot reintroduce them to the wild.

There are species like the national animal of Panama, the Panamanian golden frog, a beautiful creature about the size of your thumb tip, that today exists only in human care.

CHF: How is climate change contributing to the spread of the frog virus?

MR. KELLY: The fungus can only thrive in a certain temperature band. As the temperature band warms and moves into higher-altitude, cooler areas, the fungus moves with it.

CHF: So the Smithsonian is protecting animals through breeding and disease research and protective cultivation.

MR. KELLY: Yes, and we do a lot of work on assisted reproduction and small population management. I'll give you an example, it’s a wonderful story of the black-footed ferret, a weasel species native to North America.

As recently as the early 1970s we thought the species had been driven extinct by ranchers’ need to reduce or eliminate prairie dogs. Prairie dogs are the food, the prey of the black-footed ferret. Unintentionally, in poisoning prairie dogs, the ranchers were killing off the black-footed ferrets, which eventually were declared extinct. Then a rancher's dog in North Dakota brought back a strange animal and the rancher thought it was a common ferret. His wife realized it was a black-footed ferret and called the state biologist. The dog took them back to the last remaining group of those ferrets, which numbered about 20 or 30. But a disease was wiping out the ferrets.

At the National Zoo one of the things we do very well is understand animal disease—70 percent of human diseases come from animals.

So, like the California condor, the decision was made to bring those remaining animals into human care. Half of them were given to a US Fish and Wildlife facility in Colorado, the other half to us at the Smithsonian. From our group of, I think, eleven, we began to breed back. One of the eleven ferrets was dying when it arrived at our Front Royal facility. Our scientists were able to collect its sperm and cryopreserve it, and 20 years after it died it became a dad. They have now been reintroduced into eight states and three countries and reestablished.

RML: That is a fantastic testimonial of the kinds of things you folks are doing.

CHF: It sounds like your work is both heart-rending and heart-warming to the extent that you are able to succeed in such efforts.

MR. KELLY: There is a lot of technology involved. Right now we are involved in reintroducing the
The scimitar-horned oryx, which are extinct in the wild in the Southern Sahara (the Sahel). They have been extinct for about 50 years, but were living in American zoos and zoos around the world as well as the United Arab Emirates. We have been working for about a decade and just reintroduced the first 25 of 500 that will go back into their habitat. All of them are fitted with satellite tracking collars so that we can understand what is happening. Are they being predated? Are they being killed by humans? Are they dying of thirst? We are struggling with battery technology to track these animals in the Sahara and areas the size of the state of Rhode Island, but that is what we do in conservation to try and keep species from extinction.

CHF: It must also be a challenge to recreate the conditions of the Sahara in Front Royal, Virginia.

MR. KELLY: Yes, it is. Fortunately, we have partners in Texas and the United Arab Emirates.

RML: I’ve been reading about the concern in agriculture about problems affecting the bee population and pollination of agricultural products. Are you involved with that at all?

MR. KELLY: A little bit. It’s not one of our areas of expertise. But you’re right, it is a huge problem.

Our scientists are working in about 25 countries around the world on various issues related to conservation.

RML: Do you speak at universities? How do you make what you are doing known to people who would benefit from it, like the college students we were talking about?

MR. KELLY: We have partnerships all around the world, like our partnership with George Mason University. I think there is lots more work to be done in letting students know that they have an opportunity to be part of a conservation solution.

We are also fortunate that the 233 accredited zoos and aquariums have 183 million visitors a year. So we get incredible penetration of visitation and we use it as a platform.

Almost every zoo and aquarium in our association is a favorite place in its town or city for families with children, and it turns out we’re one of the best places for first dates. One of the reasons is because we’re safe, but we’re also places where ethics and morality are discussed, both consciously and unconsciously, in terms of why we are on this planet and what we can do to serve it.

What we need to do more of is make sure our message gets out. The vast majority of AZA-accredited institutions have shifted their mission toward the urgent crisis of extinction. At the National Zoo, with 2½ million visitors a year, our mission is to save species from extinction.

Right now we have an art installation called Washed Ashore. It is sculptures of animals, 10–15 feet tall, made out of debris from the oceans, mostly plastic waste.

CHF: What are some of the criteria for AZA accreditation?

MR. KELLY: Animal welfare and safety are the two primary ones, but there is also a strong education component and increasingly a strong conservation component. It is an intensive process that occurs every 5 years. There is usually a year’s preparation culminating, in our case, in a 5-day onsite inspection.

CHF: Do you do a lot of international travel?

MR. KELLY: Yes. I have been deeply involved in the giant panda program for about 14 years, so I find myself in China usually once a year. And we just signed a relationship with India to help them upgrade their zoos, which are much more tightly controlled by the government. The government has been systematically shutting down small for-profit zoos and building up the nonprofit zoos with a focus on conservation. I have a team that just got back from India, and I was there myself a month ago.

Our scientists are working in about 25 countries around the world on various issues related to conservation. We are part of a network, whether it is the World Wildlife Fund or Wildlife Conservation Society out of New York, or Conservation International, the Zoological Society of London, or the Zoological Society of London, or the San Diego Zoo Global, or the Singapore zoos or Australian zoos. We are all working feverishly to try and save species from extinction.

RML: Does politics enter into any of the conversations? Politics related to global climate change or any other aspect of the things that are happening?

MR. KELLY: Sure. We will be attending a global capstone congress associated with biodiversity, the Inter-
national Union of Conservation of Nature, a United Nations organization. Its meeting is this fall in Hawaii. Between 15 and 20 of our scientists will be there working on those global issues. We also are bound by the CITES treaty, the Convention on International Trade in Endangered Species of Flora and Fauna.

A lot of my colleagues get involved on issues like ivory. In 2013, 96 elephants a day were being killed for their ivory. That number has been cut in half, but still about 50 elephants a day are killed for their ivory. This practice has brought the African elephant population down from over a million to fewer than 300,000 African elephants.

RML: Are there equivalent organizations in areas where there has been great unrest, for example in Syria or Iraq, that part of the world? If so, how are they managing all of this?

MR. KELLY: The living collections unfortunately are usually decimated or moved out fairly quickly. My colleagues at the Smithsonian work on preserving the history and culture of countries, whether it is Haiti after the earthquake or Syria.

The Smithsonian cares for 146 million things. We are very good at curating living and dead things forever. It is wonderful to be part of such a sterling organization as the Smithsonian that works on preservation. Part of the difference with the National Zoo is that our things are living and we need to make sure that they stay living and stay robust as species.

RML: I said when we began this conversation that we were interested in engineers who are affecting the culture of the nation. But it is clear that what you do affects the culture not only of the nation but the world—in terms of the young people who visit your zoo, the scientists and engineers who are involved in the conservation effort, and the help to nature that you provide by researching some of the conservation issues.

MR. KELLY: One of our challenges is that we know we are losing biodiversity on our planet, the biodiversity that we evolved with over the last 7 million years. We as a species are very young. But if we are losing the biodiversity of the planet that we coevolved with over the past 7 million years, it is going to impact our air, our water, our food, our fiber. There are consequences to the loss of biodiversity that we don’t even know yet.

Our belief, as people who think in terms of processes and systems, is that the loss of biodiversity is going to have negative unintended consequences on our planet and on the ability of our planet to sustain the species that we coevolved with. That is why we are fighting so hard to preserve biodiversity.

I direct you to the story of Yellowstone when they reintroduced the grey wolf. It’s a terrific story. When they reintroduced the grey wolf back into Yellowstone, the elk, which had been free-ranging all over the park, went back to their normal nature of staying closer in smaller herds to protect themselves from predation. When they did that they were forced to stay away from the streams and not eat the tender willow shoots and other tree species coming up. Those trees came back. And when they did the beaver came back, and when the beavers came back they began to terraform the streams and the trout came back.

So when the wolf came back, through this cascade of impacts came unintended consequences of restoring native trout back to streams where they had been extinct for decades.

RML: One of my favorite topics these days is the unintended consequences of science and engineering. Usually they are considered adverse. What you have just described is a great demonstration of unintended consequences that are for everyone’s benefit.

CHF: As we near the conclusion of our conversation, Dennis, is there any message that you might like to convey to the NAE members or Congress or any of the 7,000 readers of The Bridge?

MR. KELLY: I would say that I do think the loss of biodiversity, and the fact that we are in the midst of the sixth great extinction, is going to require innovative solutions. I think engineers and scientists have a unique responsibility to help solve and mitigate these problems of loss of biodiversity. I believe the loss of biodiversity is going to make our planet less habitable, less sustainable, and we all have to work together.

RML: That is a great message.

CHF: Thank you.

MR. KELLY: I have enjoyed talking with you all.
The 2015 National Medal of Science Laureates and 2015 National Medal of Technology and Innovation Laureates received their medals from President Obama on May 19, 2016, at a White House ceremony. The medals are the nation’s highest honors for achievement and leadership in advancing the fields of science and technology.

In announcing the laureates, President Obama said, “Science and technology are fundamental to solving some of our nation’s biggest challenges. The knowledge produced by these Americans today will carry our country’s legacy of innovation forward and continue to help countless others around the world. Their work is a testament to American ingenuity.” Nine NAE members were among the 17 recipients of these prestigious awards.

The Medal of Science recognizes individuals who have made outstanding contributions to science and engineering. Shirley Ann Jackson, president, Rensselaer Polytechnic Institute: “for her insightful work in condensed matter physics and particle physics, for her science-rooted public policy achievements, and for her inspiration to the next generation of professionals in the science, technology, engineering, and math fields.”

Rakesh K. Jain, Andrew Werk Cook Professor of Radiation Oncology (Tumor Biology) and director, Edwin L. Steele Laboratory, Harvard Medical School and Massachusetts General Hospital: “for pioneering research at the interface of engineering and oncology, including tumor microenvironment, drug delivery, and imaging, and for groundbreaking discoveries of principles leading to the development and novel use of drugs for treatment of cancer and noncancerous diseases.”

The National Medal of Technology and Innovation recognizes those who have made lasting contributions to America’s competitiveness and quality of life and helped strengthen the nation’s technological workforce. Of the eight medals awarded, seven were given to NAE members.

Joseph M. DeSimone, Chancellor’s Eminent Professor of Chemistry, University of North Carolina at Chapel Hill, William R. Kenan Jr. Distinguished Professor of Chemical Engineering, North Carolina State University, and cofounder, Carbon3D: “for pioneering innovations in material science that led to the development of technologies in diverse fields from manufacturing to medicine; and for innovative and inclusive leadership in higher education and entrepreneurship.”

Robert E. Fischell, chair and president, Fischell Biomedical LLC, and professor of practice, University of Maryland at College Park: “for invention of novel medical devices used in the treatment of many illnesses thereby improving the health and saving the lives of millions of patients around the world.”
Arthur C. Gossard, professor of materials, electrical and computer engineering, University of California, Santa Barbara: “for innovation, development, and application of artificially structured quantum materials critical to ultrahigh performance semiconductor device technology used in today’s digital infrastructure.”

Chenming Hu, TSMC Distinguished Professor Emeritus, University of California, Berkeley: “for pioneering innovations in microelectronics including reliability technologies, the first industry-standard model for circuit design, and the first 3-dimensional transistors, which radically advanced semiconductor technology.”

Mark S. Humayun, Cornelius J. Pings Chair in Biomedical Sciences; professor of ophthalmology, biomedical engineering and cell and neurobiology; director, Institute for Biomedical Therapeutics; and codirector, USC Eye Institute, University of Southern California: “for the invention, development, and application of bioelectronics in medicine, including a retinal prosthesis for restoring vision to the blind, thereby significantly improving patients’ quality of life.”

Cato T. Laurencin, University Professor; Albert and Wilda Van Dusen Distinguished Professor of Orthopaedic Surgery; director, Institute for Regenerative Engineering; and director, Raymond and Beverly Sackler Center, University of Connecticut Health Center: “for seminal work in the engineering of musculoskeletal tissues, especially for revolutionary achievements in the design of bone matrices and ligament regeneration; and for extraordinary work in promoting diversity and excellence in science.”

Jonathan M. Rothberg, chair, 4catalyst Corporation, and adjunct professor of research of genetics, Yale School of Medicine: “for pioneering inventions and commercialization of next generation DNA sequencing technologies, making access to genomic information easier, faster, and more cost-effective for researchers around the world.”
Frances H. Arnold, Dick and Barbara Dickinson Professor of Chemical Engineering and Biochemistry, California Institute of Technology, has won the Millennium Technology Prize from the Technology Academy Finland. She won the $1.1 million prize for her pioneering work on directed evolution, a method of creating specific traits in enzymes.

Zdenek P. Bazant, McCormick Institute Professor and W.P. Murphy Professor of Civil and Mechanical Engineering and Materials Science, Northwestern University, was presented the Austrian Cross of Honor for Science and Art, First Class by President Heinz Fischer of Austria on May 11. The award, established in 1955, is bestowed on both Austrians and non-Austrians who have distinguished themselves and earned general acclaim through superior creative and commendable services in the sciences or arts.

Paul F. Boulos, president, COO, and CIO, Innovyze, has been selected by the American Society of Civil Engineers to receive the 2016 Parcel-Sverdrup Civil Engineering Management Award. The award ceremony will be held during the Society’s Annual Convention in Portland, Oregon, September 28–October 1. He was selected “for his business leadership, entrepreneurship and philanthropy, and his management expertise and innovation at MWH Global and Innovyze.” Dr. Boulos was also selected for a Special Distinction Award by the American Academy of Water Resources Engineers. The AAWRE president stated: “Dr. Boulos is recognized as one of the leading experts on computational hydraulics and water resources and navigation engineering in the world. As an educator, entrepreneur, and business leader, he has certainly made a remarkable contribution to the science of water and wastewater engineering.”

Joseph M. DeSimone, Chancellor’s Eminent Professor of Chemistry, University of North Carolina at Chapel Hill, is the recipient of Virginia Tech’s 2016 University Distinguished Achievement Award. The award, presented each year at commencement, recognizes achievements of national distinction in any field of enduring significance to society. Dr. DeSimone is also the CEO and co-founder of Carbon, a company focusing on advancing the 3-D printing industry into manufacturing.

Nicholas M. Donofrio, NMD Consulting, LLC, and IBM Fellow Emeritus, International Business Machines Corporation (retired), has been inducted into the Connecticut Academy of Science and Engineering.

Eric Horvitz, Distinguished Scientist and director, Microsoft Research, is the recipient of the ACM-NSF Allen Newell Award, which is presented to an individual for career contributions that have breadth in the computer sciences or that bridge the computer sciences and other disciplines.

Ahsan Kareem, Robert M. Moran Professor of Engineering, University of Notre Dame, has been awarded the 2016 Alfred Noble Prize by the American Society of Civil Engineers. This prestigious award is presented by the society to recognize a technical paper of exceptional merit. Dr. Kareem will receive the award on September 30 at ASCE’s Annual Convention in Portland, Oregon. The award is presented for his paper “Revisiting Convolution Scheme in Bridge Aerodynamics: Comparison of Step and Impulse Response Functions.”

Ross E. McKinney, professor emeritus, University of Kansas, received a 2016 Distinguished Engineering Service Award from the University of Kansas. The award honors KU engineering alumni or engineers who have maintained a close association with the university for outstanding contributions to the profession of engineering and society.

Chad A. Mirkin, director, International Institute for Nanotechnology, and George B. Rathman Professor of Chemistry, Northwestern University, received the international 2016 Dan David Prize in the Future Time Dimension at an awards ceremony May 22 at Tel Aviv University. Professor Mirkin was honored “for his innovative research in nanotechnology and medicine, which holds great promise for improvement of our world.” The prize specifically recognizes his invention of spherical nucleic acids, which couple human DNA and nanotechnology and could improve diagnostics and medical treatments.

George F. Pinder, director, Research Center for Groundwater Remediation Design, and professor of civil and environmental engineering, University of Vermont, has won a Lifetime Achievement Award from the Environmental and Water Resources Institute, a
division of the American Society of Civil Engineers. The award is given to individuals who have made a significant contribution to their field over the course of their careers. Dr. Pinder was honored at a ceremony in West Palm Beach, Florida, on May 23.

Arati Prabhakar, director, US Defense Advanced Research Projects Agency, received the Robert Fletcher Award, given annually to a graduate or friend of the Thayer School of Engineering at Dartmouth in recognition of distinguished achievement and service in the highest tradition of the school.

Calvin Quate, Leland T. Edwards Professor of Engineering Emeritus, Stanford University, shared the Kavli Prize in Nanoscience with Gerd Binnig, former member of IBM Zurich Research Laboratory, and Christoph Gerber, University of Basel. They received the prize “for the invention and realization of atomic force microscopy, a breakthrough in measurement technology and nanosculpting that continues to have a transformative impact on nanoscience and technology.” The atomic force microscope reported by Binnig, Gerber, and Quate in 1986 has since evolved dramatically and is widely used as a versatile tool for imaging and manipulation in a broad range of scientific disciplines. The Kavli Prize, awarded by the Norwegian Academy of Science and Letters, consists of a cash award of $1 million dollars in each field, a gold medal, and a scroll.

Ares J. Rosakis, Theodore von Karman Professor of Aeronautics and chair, Division of Engineering and Applied Science, California Institute of Technology, has been awarded the 2016 Theodore von Karman Medal by the American Society of Civil Engineers. It is the highest national medal awarded in the field of engineering mechanics.

The Chester Paul Siess Award for Excellence in Structural Research was presented to Yihai Bao, H.S. Lew, Santiago Pujol, and Mete A. Sozen at the ACI Concrete Convention and Exposition in Milwaukee, April 17. Dr. Sozen is the Kettelhut Distinguished Professor of Structural Engineering at Purdue University.

This year’s Julius Springer Prize for Applied Physics for outstanding research in materials science and its applications was awarded to Roland Wiesendanger and Xiang Zhang. The award was presented during the Julius Springer Forum on Applied Physics in Hamburg on May 27. Dr. Zhang, Ernest S. Kuh Endowed Chair Professor and director of the Nanoscale Science and Engineering Center at the University of California, Berkeley, received the award for his pioneering work on optical metamaterials and nanophotonics.

Two NAE members have been inducted posthumously to the National Mining Hall of Fame. Haydn H. Murray, professor emeritus, Department of Geological Sciences, Indiana University, was an internationally recognized expert on applied clay mineralogy and was without peer in his familiarity with clay mineral deposits worldwide. William N. Poundstone, retired executive vice president, Consolidation Coal Company, was recognized for his contributions to the development of improved underground coal mining technology. Individuals are selected for being leaders, innovators, authors, mentors, and philanthropists whose contributions have had significant and lasting impacts on the mineral and mining industry. Frank F. Aplan, Distinguished Professor Emeritus of Metallurgy and Mineral Processing, Pennsylvania State University, was inducted in 2015 for being one of the most influential mineral processing leaders in both industry and academia, whose studies of the processes involved in the preparation of coal and ores are acknowledged worldwide for their broad applicability.
The BRIDGE

Founding NAE Member Simon Ramo (1913–2016)

Simon Ramo

Simon Ramo, engineer, entrepreneur, pioneer in aerospace and electronics, and chief architect of the US intercontinental ballistic missile (ICBM) system, died June 27 in Santa Monica at the age of 103. He was the last living founder and original member of the NAE. The Academy’s Simon Ramo Founders Award was renamed in his honor in 2013 on the occasion of his 100th birthday.

He was born in Salt Lake City on May 7, 1913. In 1933 he earned a bachelor of science in electrical engineering from the University of Utah, and in 1936, at age 23, his PhD, magna cum laude, from Caltech with dual degrees in physics and electrical engineering.

He started out as an electrical engineer at General Electric, and in 1946 joined Hughes Aircraft Company, where he developed radar, navigation, computer, and other electronics systems for aircraft. In 1953 he left Hughes Aircraft and, with his former classmate Dean E. Wooldridge, established the Ramo-Wooldridge Corporation. He was called personally by President Eisenhower, who tasked him with creating the ICBM system, the nation’s highest priority for security according to the president. Ramo-Wooldridge merged with Thompson Products in 1958 and ultimately became TRW.

Dr. Ramo went on to create TRW’s Space Technology Laboratories, which won NASA’s first spacecraft contract and built the Pioneer 1 probe, the first spacecraft launched, in 1958, by the newly created NASA. TRW was sold to Northrop Grumman in 2002 for $7.8 billion, a deal that Dr. Ramo brokered and maintained the dominant presence of the aerospace industry in California.

He also cofounded, in 1964, the Bunker-Ramo Corporation, which produced the first version of the National Association of Securities Dealers’ Automated Quotations (NASDAQ) system.

Dr. Ramo accumulated 25 patents before turning 30. He was a pioneer in microwave transmission and detection equipment, developed GE’s electron microscope, and was the first researcher in the US to produce microwave pulses at the kilowatt level. And he remained rigorously active: In December 2013 he was awarded patent no. 8,606,170 for a computer-based learning invention, making him, at 100 years old, the oldest person to ever receive a US patent.

Dr. Ramo applied a systems approach to problem solving and used it to build rockets, cofound two Fortune 500 companies—and develop a tennis strategy that he expanded into a successful book, Extraordinary Tennis for the Ordinary Player. His textbook Fields and Waves in Communication Electronics has sold more than a million copies and is still used in more than 100 colleges and universities.

He served on the National Science Board, the White House Council on Energy R&D, the Advisory Council to the Secretary of Commerce, and the Advisory Council to the Secretary of State for Science and Foreign Affairs. He chaired Gerald Ford’s President’s Advisory Committee on Science and Technology and was Science Advisor to the President of the Republic of China under Ronald Reagan.

Among his many honors, he was awarded the Presidential Medal of Freedom in 1983, when he also became the first recipient of the NAE’s Arthur M. Bueche Award for statesmanship in national science and technology policy. He was selected for the National Medal of Science in 1979 and the Founders Medal of the Institute of Electrical and Electronics Engineers in 1980. And in addition to his NAE membership, he was a member of the National Academy of Sciences, American Academy of Arts and Sciences, and American Philosophical Society.

In the early days of the NAE he served on the Committee on Public Engineering Policy (1966–1968) and Advisory Committee to the Department of Housing and Urban Development (1969–1970), as well as the internal Committee on Membership (1964–1967), Finance Committee (1964–1967), and Council (1967–1970).

His wife of 72 years, Virginia (née Smith), died in 2009. He is survived by sons James and Alan, four granddaughters, and three great-grandchildren.

Adapted from obituaries in the New York Times (June 29) and Pasadena Now (June 28).
Battelle, Ohio State Host NAE Regional Meeting on STEM Workforce Diversity

On May 3 national science and engineering leaders converged in Columbus to discuss how the United States can better prepare the nation’s workforce for a highly competitive and increasingly knowledge-driven global economy—and how to ensure that no one is left out.

Hosted by the Ohio State University and Battelle Memorial Institute, the National Academy of Engineering regional meeting attracted nearly 200 from academia and industry to explore solutions in STEM education accessibility and diversity. Speakers included France Córdova, director of the National Science Foundation; NAE president C. D. Mote, Jr.; Michael V. Drake, Ohio State University president; and retired US Air Force Major General Suzanne Vautrinot.

The NAE launched regional meetings 16 years ago both to share initiatives with those outside its Washington, DC, headquarters and to observe engineering activity and innovations in situ.

In his opening remarks, Mote noted the symmetry of the event’s focus with the new NAE strategic plan. “It’s only the second strategic plan in the Academy’s history, and among its six goals are to increase the representation of women and underrepresented minorities and to promote and inspire competitive engineering talent in the US workforce.”

Córdova added that many NSF programs are focused on broadening participation, such as the Louis Stokes Alliances for Minority Participation (LSAMP) and NSF INCLUDES (Inclusion across the Nation of Communities of Learners of Underrepresented Discoverers in Engineering and Science); Ohio State is one of 10 institutions in the Ohio LSAMP Alliance.

“Creating the STEM workforce of the future means that we have to tap into the innovation that’s inherent in our nation’s diversity,” she said, “and we can no longer leave anyone behind.”

Panels featuring experts from Pacific Northwest National Laboratory, Toyota, and Project Lead the Way, among others, shared best practices in STEM education for students ages 5 to 25.

Aimee Kennedy, Battelle Vice President for Education, STEM Learning, and Philanthropy, said that education “is a problem worth solving” and advocated for companies and nonprofits to actively engage in the conversation on workforce preparedness and diversity.

The day before the symposium, NAE officials and others toured Metro Early College High School, a public STEM school established by Battelle and Ohio State in 2006. Members also attended a technology showcase and dinner at Battelle that evening, where they viewed some of the current technologies Battelle has developed.

Panelists (l to r) Mary Caitlyn Ricker (American Federation of Teachers), William White (Project Lead the Way), Aimee Kennedy (Battelle), and Annalies Corbin (PAST Foundation).
Nearly 200 engineers from across the Midwest and the nation converged at the University of Michigan (U-M) on May 24–25 to learn about the state of the art in autonomous and connected vehicles. Presenters also looked ahead to the challenges and benefits that will accompany the adoption of these rapidly maturing technologies.

U-M is a hub of research on autonomous and connected vehicles, collaborating with both leading automakers and government entities to advance the technology from multiple angles. Ultimately, the university and its partners plan to deploy in Ann Arbor vehicles that provide an on-demand mobility service. Attendees toured Mcity, the connected and automated vehicle test environment at U-M where self-driving vehicles can be evaluated on their handling of challenges such as traffic lights, roundabouts, and pedestrians darting into the road.

The symposium session topics were driverless cars, connected cars and communities, the potential benefits of connected and automated transportation, harnessing big data for transportation, and cybersecurity threats that these technologies could bring about.

The meeting opened with welcome remarks from Huei Peng, cochair and director of the U-M Mobility Transformation Center, which operates Mcity; Jack Hu, cochair and U-M vice president for research; and C. D. Mote, Jr., NAE president.

The driverless car session covered technologies behind self-driving vehicles, such as computer vision and map building. In the connected cars and communities session, panelists discussed how cars that communicate with one another and with surrounding infrastructure could prevent collisions and keep traffic moving more efficiently.

Some of this futuristic technology is already edging into the present. “Driver assistance systems have been available on production vehicles and they are expected to become widely available on the majority of vehicles in the US market over the next several years,” said Peng.

In the session on societal benefits, presenters talked about how advanced mobility systems could save lives, enable people to turn driving time into work or recreation time, and perhaps even lead to fleets of on-demand, electric, autonomous vehicles.

Such fleets could entice Americans into more energy-efficient travel choices, which could, in turn, reduce US dependence on foreign oil, argued Robbie Diamond, founder and CEO of Securing America’s Future Energy (SAFE). He urged governments to make regulations more consistent from state to state and to allow limited deployments of autonomous vehicles before they’re ready to be rolled out nationwide.

“Autonomous cars don’t have to work everywhere right away,” Diamond said. “There’s a ton of places that these vehicles can go, whether they’re only in gated communities to start, [or] only in the southern part of the United States. For us, it’s really about getting them on the road.”

The day closed with a keynote address by Kenneth Washington, vice president of research and advanced engineering at Ford Motor Company. He gave an overview of Ford’s self-driving car program, the first to demonstrate fully autonomous driving at night and in snow. The snow testing was conducted at Mcity.
Day two opened with a session on big data for transportation. Donald Brown, director of the Data Science Institute at the University of Virginia, discussed his lab’s work using natural language processing to mine tweets and predict hit-and-run accidents.

“Want to guess the sort of tweets that predict an accident?” Brown asked. “‘I’m stuck in traffic.’ ‘Things are really congested.’ ‘There’s construction up ahead.’ ‘I’m going to be late.’ ‘I’m delayed and I’m irritated.’ If you see any of those, within about an hour somebody will do something like scrape a car.”

In the final session, on cybersecurity, presenters said this issue isn’t getting the attention it deserves. Kang Shin, a professor of electrical engineering and computer science at U-M, warned that with current technologies, “adversaries don’t have to be experts.” Receivers in most vehicles don’t have a way to ensure that incoming instructions come from a trusted source, he said.

“There’s never going to be a way to totally protect a system from attack,” added Suzanne Lightman, senior advisor for information security at the National Institute of Standards and Technology. “It just has to keep functioning.” Automobile manufacturers will need to come to grips with this new reality.

“Autonomous and connected vehicles are going to change how we live and how we get around as a society. With our specialized understanding of complex systems, engineers can play a key role in ensuring that these technologies are integrated into the fabric of our lives most effectively and safely,” said Professor Alec Gallimore, the Robert J. Vlasic Dean of Engineering at U-M.

The 2016 Japan-America Frontiers of Engineering Symposium (JAFOE) was held June 16–18 at the Arnold and Mabel Beckman Center in Irvine. NAE partners with the Engineering Academy of Japan to carry out this activity. NAE member Steven DenBaars, professor of materials and codirector of the Solid State Lighting and Energy Electronics Center at the University of California, Santa Barbara, and Yoshikazu Nakajima, associate professor of bioengineering and mechanical engineering at the University of Tokyo, cochaired the symposium.

The 2016 JAFOE symposium was attended by 60 earlier-career engineers from US and Japanese universities, companies, and government labs who discussed leading-edge developments in four engineering fields: urban mobility efficiency, nanotechnology in energy storage and conversion, additive manufacturing, and big data.

Urban mobility faces several major issues, including system reliability and resilience; unsustainable impacts on energy, climate, and the environment; inadequate funding sources; lagging innovation and research; and accessibility for elderly and disabled persons. This session focused on a future vision of urban structure and human activity—travel behavior and quality of life in the ICT age. Talks covered the impact of autonomous vehicles on equity and mobility; the socioeconomic context of future cities and mobility in an aging, urban society; the
relationship among social networks, the built environment, and travel behavior; and travel impacts of connected, autonomous, app-driven vehicles and services.

The session on Nanotechnology in Energy Storage and Conversion focused on how nanotechnology can bring benefits in energy generation, storage, and efficiency. The first speaker discussed the use of nanotechnology for the formation of nanocomposite materials for batteries and supercapacitors, thereby achieving a unique combination of higher energy density, stability, rate performance, and, in some cases, multifunctionality in such devices. The next speaker described how advanced diagnosis and nanomanufacturing could make an impact on advancing energy storage technology for electric vehicles and storage for renewables. This was followed by a talk on engineered biocatalysts and nanostructured porous carbon electrode materials to design new biosensing systems with higher accuracy and biofuel cells with higher power density. The session concluded with a talk on the use of NEMS/MEMS technology for the creation of flexible devices using rigid materials for displays, sensors, batteries, and solar cells.

The third session, on additive manufacturing, presented the cutting-edge research needed to bring 3D printing to integrated advanced manufacturing, focusing primarily on four critical components: hardware, materials, data, and infrastructure. The session also covered ways the technology revolutionizes conventional manufacturing and its influence on society. The first two talks focused on the physical world, capturing how new materials and equipment can provide unique properties, citing the examples of 3D designable gels and hybrid materials and structures. The second two talks delved into the virtual world, exploring how data and computational infrastructure can change the way we design and qualify additive components. Here the speakers discussed how deep learning neural networks facilitate new user interfaces connecting design, engineering, manufacturing, and testing, and how computational tools provide a framework for understanding additive processes to meet the stringent demands of manufacturing components for aircraft.

The symposium concluded with a session on big data, insights from which enable better decision making and greater operational efficiency. However, to meaningfully extract value from data, big data technology will need to infuse analytics into systems, sensors, and devices while protecting security and privacy—challenges that need to be taken into account from the conception of all big data infrastructure. Reflecting the breadth of this rapidly expanding field, the four talks in the session covered big data analysis to assist in practical decision making, data mining and privacy, how the concept of differential privacy can be useful for preserving validity in adaptive data analysis, and reliable incorporation of data into database technology for the Internet of Things.

In addition to the formal sessions, a poster session preceded by flash poster talks was held on the first afternoon. This served as both an icebreaker and an opportunity for all participants to share information about their research and technical work. The posters were left up throughout the meeting, facilitating further discussion and exchange during the coffee breaks. On the second afternoon, attendees were taken to Laguna Beach for a walking tour in beautiful southern California coast.

It is an FOE tradition to have the dinner speech on the first evening of the meeting given by a senior-level individual from industry, government, or academia. At this meeting, the Hon. Jeff Bingaman, former senator of New Mexico, gave the dinner speech, titled “The Role of Public Policy in Technology Development and Deployment.” He described shared US-Japan objectives in the energy arena—producing nuclear power safely, increasing production from renewable energy, and achieving greater energy efficiency—and the commonalities and differences in the two countries’ approaches. He also commented on the role of public policy in technology development and deployment in the larger context of Japanese and US energy goals, namely, safety, security, efficiency, and environmental protection. In concluding his talk, Senator Bingaman noted that neither the United States nor Japan is doing enough in this area, that we should learn from each other, and that new technologies are needed to reach our energy goals.

Funding for this activity was provided by The Grainger Foundation and the Japan Science and Technology Agency. The next JAFOE symposium will be held in 2018 in Japan.

NAE has been holding Frontiers of Engineering symposia since 1995. For more information about this meeting and the symposium series, visit www.naefrontiers.org. To nominate an outstanding engineer to participate in future Frontiers meetings, contact Janet Hunziker at JHunziker@nae.edu.
New NAE Staff

ROHAIFA H. ALAFRANGY joined the NAE leadership team as membership associate on April 18. She works closely with the Membership Office and the in-house IT staff to ensure that the membership records are maintained accurately and updated in a timely manner. With 10 years of IT experience in government and private industry, she has extensive experience with databases and is familiar with various reporting tools. She has most recently worked part time at the World Bank as a public relations liaison. She also has been a contract employee for a computer company that supports the armed forces. Rohaifa earned a master’s in linguistics from George Mason University and a bachelor’s from Ajman University in the United Arab Emirates. She succeeds Jenney Resch who had served in the membership office since August 2009.

CARL-GUSTAV ANDERSON joined the Program Office on January 11, with more than six years of administrative and research experience at the National Academies, having served with the Board on Life Sciences and the Board on Chemical Sciences and Technology. He is program coordinator for activities of the NAE’s Center for Engineering Ethics and Society, several projects in our engineering education/workforce portfolio, and the NAE’s annual E4U video contest. Carl brings considerable administrative, research, and writing skills and experience to the job and a particular interest in engineering and science ethics. He earned his master’s and BA degrees in philosophy from American University.

MICHAEL HAMILTON is the membership/elections associate in the NAE Membership Office. He brings a range of database management and web technology skills, and comprehensive knowledge of association operations with more than 10 years of experience in logistical management and planning for committee, section, and board events. Having worked as NAE membership elections assistant from May 2006 to December 2008, he resumes many of his former support and coordinator duties for the organization’s program to annually nominate, evaluate, and elect members and foreign members. He will also assist with the development of promotional material for publication.

MICHAEL HOLZER is a senior program assistant to our Awards Program and our Program on Manufacturing, Design, and Innovation. He joined the Program Office on November 16, 2015. He brings administrative, research, and technical writing skills and experience developed in his previous work for the National Coalition for Homeless Veterans, Tantus Technologies Inc., Health Assistance Partnership, and his graduate studies. Michael earned his master’s of public policy, health and social policy at the Trachtenberg School of Public Policy at George Washington University and his BA in English at University of Maryland at College Park.
KENAN (KEN) JARBOE leads the NAE program on Manufacturing, Design, and Innovation. He comes to the NAE from Athena Alliance, a research and public policy nonprofit dedicated to exploring the I-Cubed (Information-Innovation-Intangibles) Economy, where he was chief executive and chief operating officer. Before founding Athena Alliance he was senior US strategist at G7 Group Inc., senior fellow at the Work and Technology Institute, and an analyst at the Congressional Office of Technology Assessment. He has also held a number of senior staff positions for the Senate, including as chief economist for the Senate Democratic Policy Committee. His consulting clients have included the National Academy of Sciences, the Congressional Joint Economic Committee, the Progressive Policy Institute, the Science and Technology Policy Institute, and the German Institut Arbeit und Technik. Ken received his PhD in sociotechnological planning and BS in engineering from the University of Michigan. He joined the Program Office on September 8, 2015.

ERVIN PINCKNEY joined the Membership Office as an assistant on June 13. He brings extensive experience in administrative work, having provided administrative support at NGP VAN as HR/operations assistant, and before that as operations associate at the Colon Cancer Alliance. At the American Land Title Association he maintained Q Production database software and website updates. Ervin will earn a BA in political science from the University of the District of Columbia in fall 2017.

KELLI ZINGLER joined the NAE leadership team as senior executive assistant to the president on November 9, 2015. Working closely with Dr. Mote, she provides advanced, confidential administrative and professional support across all responsibilities of the president. Kelli comes with extensive professional experience in government and private industry. Before coming to the NAE she was executive assistant to the director of the Smithsonian American Art Museum, in Washington; her duties included operation of the director's office, serving as liaison to the museum’s board of commissioners, and the planning and coordination of logistics and materials for all board meetings and activities. She reviewed or prepared and coordinated all correspondence for the director’s signature and provided the director and museum supporters with timely, executive-level assistance. In earlier positions she was assistant to the director of the Chrysler Museum of Art in Norfolk, Virginia, and assistant to the president of the Air Line Pilots’ Association, in Washington, DC, a professional association with 40,000+ members. Kelli earned her BA in political science at the University of Delaware.

**Bainum Family Foundation Intern Joins the Program Office**

During the summer of 2016 the NAE Program Office hosted Bainum Family Foundation intern PHILLIP TAYLOR COLEMAN, who performed community management duties for the LinkEngineering website project. His work included extensive outreach to current and potential new members of the site, which aims to support preK–12 educators, professional development providers, and administrators in implementing engineering education. Taylor is a rising junior studying mechanical engineering at Andrews University in Berrien Springs, Michigan. In his sophomore year, he participated as part of a school team in SpaceX’s Hyperloop pod competition and was active in Engineers Without Borders. He is interested in engineering policy and wants to use engineering for humanitarian projects. When not in school or working, Taylor enjoys playing classical piano and watching movies.
Daniel Berg (NAE '76) has long been an active member and generous supporter of the National Academy of Engineering. This year marks his 40th anniversary as a member, and to celebrate he is “giving big” and joining the ranks of the Academies’ Einstein Society, whose members’ cumulative lifetime giving is $100,000 or more. In addition, he has joined the Academies’ Heritage Society by naming the NAE as a beneficiary of his estate.

“The NAE has made an enormous impact on me as a professional. This is an opportune time to do something bigger,” Berg explained. “I’ve been hoping to become an Einstein member. I thought this would be a nice time to recognize both the organization’s meaning to me and what the NAE does—not only for the country but for the world.”

Over the years, the NAE has provided countless opportunities that helped him advance professionally, Berg said. A former president of Rensselaer Polytechnic Institute, he first encountered his predecessor in that position, George Low, at the NAE. “He gave a talk when he won [the Founders Medal].” Although they didn’t meet then, “a couple of years later, he hired me as provost. I truly believe the NAE has helped me in my career—not only through the connections I’ve made but also by broadening my scope and getting me involved in new things.”

Even more important, he says, is the opportunity to support the NAE’s work. “For a relatively small budget, the NAE’s impact is incredible. Dollar for dollar, it’s a very high return on your investment. It’s an organization that provides advice that is grounded in study and analysis. The goal is to do the right thing for society.”

For additional information or to make gift in honor of someone or to celebrate a special occasion, please contact Radka Nebesky at 202.334.3417 or RNebesky@nae.edu.
In Memoriam

J. DAVID HELLUMS, 86, A.J. Hartsook Professor Emeritus, Rice University, died June 26, 2016. Dr. Hellums was elected to the NAE in 1998 for the application of biofluid mechanics and cellular engineering methods to biological research and education.

WOODROW E. JOHNSON, 97, retired vice president and senior consultant, Westinghouse Electric Corporation, died August 1, 2015. Dr. Johnson was elected to the NAE in 1968 for design of nuclear reactor systems for defense, power generation, and scientific research.

SALOMON LEVY, 89, founder, Levy & Associates; retired CEO and president, S. Levy Inc.; and retired general manager, Boiling Water Reactor Operations, General Electric Company, died March 23, 2016. Dr. Levy was elected to the NAE in 1974 for contributions to development of nuclear systems for high-performance boiling water reactors.

BILL B. MAY, 80, retired chair and CEO, ARGOSystems Inc., died June 6, 2016. Dr. May was elected to the NAE in 1988 for outstanding accomplishments in pioneering and bringing to practice significant electronic surveillance technologies.

JOHN P. McTAGUE, 74, retired professor, materials, University of California, Santa Barbara, died June 7, 2014. Dr. McTague was elected to the NAE in 1998 for oversight and implementation of technical transfer in the national laboratories and leadership in automotive development.

BENJAMIN F. MONTOYA, 80, Rear Admiral, Civil Engineer Corps, US Navy, retired, died December 19, 2015. Dr. Montoya was elected to the NAE in 2001 for environmental and organizational leadership in both the US Navy and public power sector while maintaining total dedication to societal values.

SIMON RAMO, 103, cofounder, TRW Inc., died June 28, 2016. Dr. Ramo was a founding member of the NAE (see p. 70).

ALLEN S. RUSSELL, 100, retired vice president and chief scientist, Aluminum Company of America, died June 16, 2016. Dr. Russell was elected to the NAE in 1976 for contributions to a new process for aluminum reduction.

SHIRLEY E. SCHWARTZ, 80, retired materials engineer, General Motors Corporation, died May 8, 2016. Dr. Schwartz was elected to the NAE in 2000 for contributions to lubrication engineering and for enriching the technical community through freelance writing.

PETER G. SIMPKINS, 81, University Professor Emeritus, Syracuse University, and Former Distinguished MTS, Bell Labs, died June 20, 2016. Dr. Simpkins was elected to the NAE in 1999 for contributions to the understanding and development of processes fundamental to the manufacture of low-loss, high-strength optical fiber.

Calendar of Events and Meetings

| September 27 | Committee on the Engagement of Engineering Societies in Undergraduate Engineering Education |
| September 30–October 1 | Convocation on Enhancing Teachers’ Voices in Policymaking for K–12 Engineering Education |
| October 7 | 2016 Grand Challenges Scholars Program Annual Meeting |
| October 7–8 | NAE Council Meeting |
| October 8 | NAE Peer Committee Meetings |
| October 9–10 | 2016 NAE ANNUAL MEETING |
| October 11–12 | Engineering R&D for a Quieter America |
| October 17–19 | EU-US Frontiers of Engineering Helsinki, Finland |
| October 11 | Fritz J. and Dolores H. Russ Prize Committee Meeting |
| December 9–10 | Committee on Membership Meeting Irvine, California |

All meetings are held in National Academies facilities in Washington, DC, unless otherwise noted.
The following reports have been published recently by the National Academy of Engineering or the National Academies of Sciences, Engineering, and Medicine. Unless otherwise noted, all publications are for sale (prepaid) from the National Academies Press (NAP), 500 Fifth Street NW–Keck 360, Washington, DC 20001. For more information or to place an order, contact NAP online (www.nap.edu) or by phone (800-624-6242). Note: Prices quoted are subject to change without notice. There is a 10 percent discount for online orders when you sign up for a MyNAP account. Add $6.50 for shipping and handling for the first book and $1.50 for each additional book. Add applicable sales tax or GST if you live in CA, CT, DC, FL, MD, NC, NY, PA, VA, WI, or Canada.

**Forum on Proposed Revisions to ABET Engineering Accreditation Commission General Criteria on Student Outcomes and Curriculum (Criteria 3 and 5): A Workshop Summary.** On February 16, 2016, the National Academy of Engineering held a forum to discuss proposed changes to criteria used by ABET (formerly the Accreditation Board for Engineering and Technology) to accredit engineering programs in colleges and universities around the world. The forum convened a variety of stakeholders in the education of engineers, including representatives of universities, industry, and professional organizations. The presenters and attendees discussed the proposed changes and related issues such as a perceived lack of communication surrounding the development of the changes and the degree to which the criteria prepare engineering students for jobs after graduation. This report summarizes the presentations and discussions at the forum.

NAE members on the planning committee were Alan Cramb (chair), president, Illinois Institute of Technology, and Mary Boyce, dean of engineering, Fu Foundation School of Engineering and Applied Science, Columbia University. Free PDF.

**Electricity Use in Rural and Islanded Communities: Summary of a Workshop.** On behalf of the Quadrennial Energy Review (QER) Task Force, the National Academies of Sciences, Engineering, and Medicine hosted a workshop on February 8–9, 2016, on electricity use in rural and islanded communities. The objective of the workshop was to help QER Task Force public outreach efforts in communities with unique electricity challenges. The workshop explored challenges and opportunities for reducing electricity use and associated greenhouse gas emissions while improving electricity system reliability and resilience in rural and islanded communities. This report summarizes the presentations and discussions at the workshop.

NAE member John G. Kassakian, professor of electrical engineering and computer science emeritus, Massachusetts Institute of Technology, was a member of the workshop planning committee. Free PDF.

**Using Graywater and Stormwater to Enhance Local Water Supplies: An Assessment of Risks, Costs, and Benefits.** Chronic and episodic water shortages are becoming common in many regions of the United States, and population growth in water-scarce regions compounds the challenges. Increasingly, alternative water sources such as graywater (untreated wastewater that does not include water from the toilet but generally includes water from bathroom sinks, showers, bathtubs, clothes washers, and laundry sinks) and stormwater (water from rainfall or snow that can be measured downstream in a pipe, culvert, or stream shortly after the precipitation event) are being viewed as resources to supplement scarce water supplies rather than as waste to be discharged. Other potential benefits of stormwater include energy savings, pollution prevention, and reduced impacts of urban development on urban streams; and graywater can enhance water supply reliability and extend the capacity of existing wastewater systems in growing cities. But limited information is available, and many state and local public health agencies have not developed regulatory frameworks for the full use of these water resources. This report analyzes the risks, costs, and benefits of various uses of gray- and stormwater and examines technical, economic, regulatory, and social issues associated with their use. The report considers the quality and suitability of water for reuse, treatment and storage technologies, and human health and environmental risks of water reuse.

NAE members on the study committee were Richard G. Luthy (chair), Silas H. Palmer Professor, Department of Civil and Environmental Engineering, Stanford University, and Glen T. Daigger,
professor of engineering practice, Department of Civil and Environmental Engineering, University of Michigan. Paper, $64.00.

Optimizing the Nation’s Investment in Academic Research: A New Regulatory Framework for the 21st Century. Research universities are critical contributors to the US research enterprise and the principal source of a first-rate labor force and fundamental discoveries that enhance lives. There is concern, however, that the unintended cumulative effect of federal regulations undercuts the productivity of the research enterprise and diminishes the return on federal investment in research. This report reviews the current regulatory framework, considers regulations that have placed undue (often unanticipated) burdens on the research enterprise, and reassesses the process by which these regulations are created, reviewed, and retired. This review can help strengthen the partnership between the federal government and research institutions, maximize the creation of new knowledge and products, provide for the effective training and education of the next generation of scholars and workers, and optimize the return on federal investment in research.

NAE member Ilesanmi Adesida, vice chancellor for academic affairs and provost, University of Illinois at Urbana-Champaign, was a member of the study committee. Paper, $65.00.

Future Directions for NSF Advanced Computing Infrastructure to Support US Science and Engineering in 2017–2020. Demand for advanced computing has been growing for all types and capabilities of systems, from large numbers of single commodity nodes to jobs requiring thousands of cores; for systems with fast interconnects; for systems with excellent data handling and management; and for increasingly diverse applications. Since the advent of its supercomputing centers, the National Science Foundation (NSF) has provided its researchers with state-of-the-art computing systems. New models of computing, including cloud computing and publicly available but privately held data repositories, open up new possibilities for NSF, which asked the National Research Council to examine anticipated priorities and associated tradeoffs for advanced computing. This report provides a framework for decision making about NSF’s advanced computing strategy and programs, with recommendations for achieving four broad goals: (1) position the US for continued leadership in science and engineering, (2) ensure that resources meet community needs, (3) aid the scientific community in keeping up with the revolution in computing, and (4) sustain the infrastructure for advanced computing. NAE member William D. Gropp, Thomas M. Siebel Chair in Computer Science, University of Illinois at Urbana-Champaign, cochaired the study committee. Paper, $48.00.

Modernizing Crime Statistics: Report 1: Defining and Classifying Crime. To derive statistics about crime—to estimate its levels and trends, assess its costs to and impacts on society, and inform law enforcement approaches to prevent it—a conceptual framework for defining and thinking about crime is essential. Developing and maintaining such a framework is no easy task, because the mechanics of crime are ever evolving, based on shifts and developments in technology, society, and legislation. Interest in understanding crime surged in the 1920s, a pivotal decade for the collection of nationwide crime statistics. The Census Bureau commissioned a manual for preparing crime statistics and suggesting a standard taxonomy of crime, intended for use by the police, corrections departments, and courts alike. The key distinction between the rigorous classification proposed in this new report and previous “classifications” in US crime statistics is that it partitions all behaviors that could be considered criminal offenses into mutually exclusive categories. The report makes recommendations for the development of modern crime measures in the United States and the best means for obtaining them. It weighs various perspectives on how crime should be defined and organized with the needs and demands of the full array of crime data users and stakeholders.

NAE member Jonathan P. Caulkkins, professor of operations research and public policy, Heinz College, Carnegie Mellon University, was a member of the study committee. Paper, $79.00.

Chemical Laboratory Safety and Security: A Guide to Developing Standard Operating Procedures. The US Department of State charged the Academies with the task of producing a protocol for the development of standard operating procedures (SOPs) to complement Chemical Laboratory Safety and Security: A Guide to Prudent Chemical Management, for inclusion with the other materials in the 2010 toolkit. A committee was appointed with experience and knowledge in good
chemical safety and security practices in academic and industrial laboratories and awareness of international standards and regulations. This expansion product is intended to enhance the use of the previous reference book and the accompanying toolkit, especially in developing countries where safety resources are scarce and the experience of operators and end users may be limited.

NAE members on the study committee were Montgomery M. Alger, director, Institute for Natural Gas Research, Pennsylvania State University, and Thomas F. Edgar, George T. and Gladys H. Abell Endowed Chair in Engineering, McKetta Department of Chemical Engineering, University of Texas at Austin. Paper, $44.00.

Effects of the Deletion of Chemical Agent Washout on Operations at the Blue Grass Chemical Agent Destruction Pilot Plant. The United States manufactured significant quantities of chemical weapons during the Cold War and the years prior. The chemical weapons are now aging, and storage constitutes a risk to the facility workforce and to the communities nearby. Moreover, the Chemical Weapons Convention stipulates that these weapons be destroyed. The United States has destroyed approximately 90 percent of its chemical weapons stockpile at seven sites. To destroy the remainder, the Department of Defense is building the Blue Grass Chemical Agent Destruction Pilot Plant (BGCAPP) on the Blue Grass Army Depot (BGAD), near Richmond, Kentucky. The stockpile at BGAD consists of rockets and projectiles containing the nerve agents GB and VX and the blister agent mustard. Because of public opposition to the use of incineration to destroy the BGAD stockpile, Congress mandated that nonincineration technologies be identified for use at BGCAPP. The original BGCAPP design called for the munitions to be drained of agent and then washed out using high-pressure hot water. But as part of a larger package of modifications called Engineering Change Proposal 87 (ECP-87), the munition washout step was eliminated. This report examines the impacts of this change on operations at BGCAPP and makes recommendations to guide future decision making.

NAE members on the study committee were Richard C. Flagan, Irma and Ross McCollum–Wm. H. Corcoran Professor of Chemical Engineering, professor of environmental science and engineering, and executive officer of chemical engineering, California Institute of Technology; Thom J. Hodgson, Distinguished University Professor, Fitts Industrial & Systems Engineering Department, North Carolina State University; and William J. Ward III, retired research engineer, GE Corporate Research and Development. Paper, $40.00.

Applying Materials State Awareness to Condition-Based Maintenance and System Life Cycle Management: Summary of a Workshop. In August 2014 the committee on Defense Materials Manufacturing and Infrastructure convened a workshop to discuss issues related to applying materials state awareness to condition-based maintenance and system life cycle management. The workshop focused on advances in three areas: (1) metrology and experimental methods, (2) physics-based models for assessment, and (3) databases and diagnostic technologies. This report summarizes the discussions and presentations at the workshop.

NAE members on the workshop planning committee were Paul J. Kern, US Army (ret.), and senior counselor, The Cohen Group, and Robert E. Schafrik, retired executive, Aviation Engineering Division, General Electric Aviation. Paper, $50.00.

Lessons Learned from the Fukushima Nuclear Accident for Improving Safety and Security of US Nuclear Plants: Phase 2. Congress asked the National Academy of Sciences to conduct a technical study on lessons learned from the Fukushima Daiichi nuclear accident for improving the safety and security of commercial nuclear power plants in the United States. This study was carried out in two phases: Phase 1 looked at the causes of the Fukushima Daiichi accident and safety-related lessons learned for improving nuclear plant systems, operations, and regulations exclusive of spent fuel storage; the report was issued in 2014. This Phase 2 report focuses on (1) lessons learned from the accident for nuclear plant security, (2) lessons learned for spent fuel storage, and (3) reevaluation of conclusions from previous Academies studies on spent fuel storage.

NAE members on the study committee were Michael L. Corradini, professor, Department of Engineering Physics, University of Wisconsin–Madison; Vijay K. Dhir, Distinguished Professor, Henry Samueli School of Engineering and Applied Science, University of California, Los Angeles; John A. Orcutt, Distinguished Professor of Geophysics, Scripps Institution of Oceanography, University of California, San Diego; and Loring
A. Wyllie Jr., senior principal and chair (ret.), Degenkolb Engineers. Paper, $65.00.

**Review of the US Global Change Research Program’s Update to the Strategic Plan Document.** The Update to the Strategic Plan (USP) is a supplement to the Ten-Year Strategic Plan of the US Global Change Research Program (USGCRP) completed in 2012. The Strategic Plan sets out a research program guiding 13 federal agencies in accord with the Global Change Research Act of 1990. This report reviews whether USGCRP’s efforts to achieve its goals and objectives, as documented in the USP, are adequate and responsive to the nation’s needs, whether the priorities for continued or increased emphasis are appropriate, and whether the document communicates effectively, all in a context of the history and trajectory of the program.

NAE member Warren M. Washington, senior scientist, Climate Change Research Section, Climate and Global Dynamics Division, National Center for Atmospheric Research, chaired the study committee. Paper, $42.00.

**Barriers and Opportunities for 2-Year and 4-Year STEM Degrees: Systemic Change to Support Students’ Diverse Pathways.** Nearly 40 percent of students entering 2- and 4-year postsecondary institutions indicated their intention to major in science, technology, engineering, or mathematics (STEM) in 2012. But about half of those who intended to earn a STEM bachelor’s degree and more than two-thirds seeking a STEM associate’s degree fail to do so 4–6 years after their enrollment. Many who do obtain a degree take longer than the advertised length of the program, raising the cost of their education. This report reviews research on the factors that influence students’ decisions to enter, stay in, or leave STEM majors—quality of instruction, grading policies, course sequences, undergraduate learning environments, student supports, students’ general academic preparedness and competence in science, family background, and governmental and institutional policies that affect STEM educational pathways. It identifies areas for further research to create a system that works for all students who aspire to STEM degrees, and it lays out steps for faculty, STEM departments, colleges and universities, professional societies, and others to improve STEM education for all students interested in a STEM degree.

NAE member Leah H. Jamieson, Ransburg Distinguished Professor of Electrical & Computer Engineering and John A. Edwardson Dean of Engineering, Purdue University, was a member of the study committee. Paper, $54.00.

**Preliminary Review of the Draft Science, Education, and Design Strategy for the Water and Environmental Research Systems (WATERS) Network.** Proper management of US water resources is a critical challenge. Water availability and quality are changing with increasing population, urbanization, and land use and climate change. Although the country’s overall water use has remained relatively constant since about 1980, shortages in water supply have been increasing in frequency in many parts of the country, and water quality is also declining in some areas. NSF has proposed the Water and Environmental Research Systems (WATERS) Network as an initiative whereby NSF could provide the advances in the basic science needed to respond effectively to the challenge of managing water resources. In this interim report the committee comments on the WATERS draft design strategy and provides advice in key categories related to the WATERS plan: science questions; observatory design; sensors; cyberinfrastructure; education and outreach; and governance and management.

NAE members on the study committee were George M. Hornberger (chair), director, Vanderbilt Institute for Energy and Environment and Distinguished University Professor, Department of Civil & Environmental Engineering, Vanderbilt University; Glen T. Daigger, senior vice president and chief technology officer, CH2M Hill Inc.; Daniel P. Loucks, professor, School of Civil and Environmental Engineering, Cornell University; and Charles R. O’Melia (deceased), Abel Wolman Professor of Environmental Engineering Emeritus, Johns Hopkins University. Free PDF.

**Continuing Innovation in Information Technology: Workshop Report.** The 2012 NRC consensus report on this topic illustrates how fundamental research in information technology (IT), conducted in industry and universities, has led to the introduction of entirely new product categories that became billion-dollar industries. The report’s “tire tracks” graphic connects areas of major investment in basic research, university-based research, and industry research and development; the introduction of important commercial products resulting from this research; billion-dollar-plus industries stemming from it; and present-day IT market segments and
representative US firms whose creation was stimulated by the decades-long research. At a 2015 workshop academic and industry researchers and industrial technologists described key research and development results and their contributions and connections to new IT products and industries, and illustrated these developments as overlays to the 2012 graphic. The principal goal of the workshop was to collect and make available to policymakers and members of the IT community first-person narratives illustrating the link between government investments in academic and industry research to the creation of new IT industries. This report summarizes the workshop presentations organized in five themes—(1) fueling the innovation pipeline, (2) building a connected world, (3) advancing the hardware foundation, (4) developing smart machines, and (5) people and computers—as well as the concluding panel discussion.

NAE members on the committee were Mark E. Dean, research chair, College of Engineering, University of Tennessee, IBM (ret.), and Barbara H. Liskov, Institute Professor, Massachusetts Institute of Technology. Paper, $45.00.

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