Reaching Students: What Research Says About Effective Instruction in Undergraduate Science and Engineering

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Thinking About Learning and Teaching as a Researcher Would

If you’re like many instructors of undergraduate science and engineering, you may be fairly satisfied with your teaching. You’ve made an effort to craft meaningful and interesting lectures that coherently present the content students should learn in your discipline. You may break up your lectures with questions that students answer anonymously on handheld devices. The students who work hard do well in your courses, and your evaluations are good, perhaps outstanding. While there are certainly things you could tweak, the other demands on your time—including, in many cases, your own research agenda—may make you hesitant to tamper with a solid course.

Or perhaps you’re a department head, faculty development expert, or institutional leader who would like to invigorate instruction on a wider scale but must consider any reforms within a broader context of faculty autonomy, time and funding constraints, and other pressing priorities. Or maybe you’re a graduate student or post-doc who would like to explore innovative teaching in your discipline but sees little incentive from your department or the competitive faculty job market to pursue those innovations.

So why take time to investigate effective approaches to teaching and learning? Why make the effort to redesign a course or program that on the whole seems to be working well? A short answer comes from the experiences of many instructors around the country—successful by standard criteria—who reviewed the research on learning, reflected on their teaching, and found it wanting. Drawing on this research base, they designed ways to help their students develop a better understanding of the fundamental concepts of a science or engineering discipline, become more engaged in their own learning, and begin to think and reason as scientists and engineers do. These instructors often started with modest changes and refined their techniques over time. And their results were often encouraging.
This chapter discusses the benefits of adopting a research-based approach to teaching and learning and introduces findings from research that are explored in greater depth in later chapters. The examples and case studies in this chapter describe the factors that motivated instructors to examine or conduct research on learning and make changes in their teaching. These cases also illustrate how research-based strategies can be feasible—exciting, even—in settings ranging from community colleges to large research institutions, and from small classes to big introductory lecture courses.

Research on Learning Spurs Changes in Teaching Practices

For Eric Mazur,¹ a professor of physics at Harvard University, the desire to change his teaching took shape in 1990, when he came across a series of papers by Ibrahim Halloun and David Hestenes (1985, 1987) showing that conventional physics instruction did little to alter students’ misguided beliefs about common physical phenomena. Although, after a few months of physics instruction, most students could correctly recite Newton’s third law and apply it in numerical problems, Halloun and Hestenes probed more deeply by administering an assessment they had developed called the Force Concept Inventory. The results suggested that many students did not truly understand basic Newtonian concepts. Mazur, who had been teaching introductory physics since 1984, doubted this was a problem for his Harvard students. But he was intrigued enough to try the test on his own science and engineering majors. “The results of the test came as a shock: the students fared hardly better on the [conceptual] test than on their midterm examination,” Mazur writes. Yet, he notes, the midterm covered material of far greater difficulty—“or so I thought” (Mazur, 1997, p. 4).

Mazur’s further research with his own students convinced him that although many could correctly solve conventional mathematics problems in physics, a sizable share continued to cling to alarming misconceptions. He concluded that many students do well on conventional problems “by memorizing algorithms without understanding the underlying physics.” Moreover, he realized, even experienced teachers could be “completely misled into thinking that students have been taught effectively” (Mazur, 1997, p. 6).

¹ Except where noted, the information in this example comes from an interview with Eric Mazur, April 13, 2013.
Following this revelation, Mazur explored different strategies for teaching introductory physics. Over time, he developed an approach called Peer Instruction, described in more detail in Chapter 4. In Peer Instruction, brief lecture presentations are interspersed with short assessment questions, or ConcepTests, designed to expose common student difficulties in understanding a single concept. Students think about the question, come up with their own answers, and then discuss their responses for a few minutes with a small group of peers as they seek to reach consensus on the correct answer (Mazur, 1997).

A self-confessed “data junkie,” Mazur analyzed years of statistics on his students’ performance and continued to refine his teaching. His data show that students taught with Peer Instruction have greater mastery of conceptual reasoning and quantitative problem-solving skills than those in traditionally taught classes (Crouch and Mazur, 2001). More recent work by Lazry, Mazur, and Watkins (2008) found similar improvements in knowledge and skills, as well as decreased attrition in introductory physics courses, among community college students taught with Peer Instruction.

For Richard Yuretich, a professor at the University of Massachusetts Amherst, the impetus to change grew out of his frustration with poor attendance and a lack of student engagement in his large oceanography course, which enrolled roughly 1,200 students. Most of the students were not science majors, and they were divided into four sections taught by different instructors. Although the course received high ratings on student evaluations, Yuretich, who at that point had been teaching for more than a decade, still felt that “the class was not being engaged on any level.” He described the problem in this way (Yuretich et al., 2001):

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2 Except where noted, the information in this example comes from an interview with Richard Yuretich, April 4, 2013.
Despite our best efforts to deliver coherent, enthusiastic, and well-illustrated lectures, we questioned whether many students were learning as much as they could. Attendance on a typical day hovered at or below 50%, except just before exams when the class was packed. Students would routinely leave early or arrive late. Our attempts to engage the class in questioning and discussion resulted in the animated participation of a small cadre of motivated students, but the rest of the class was listless and disinterested.

Yuretich wanted to teach in a way that would convince students that “if they come to class, this is where learning is going to happen.” A new center for learning on his campus had begun giving workshops on more interactive approaches to teaching, which inspired him to try something new. At that time, in the 1990s, research on geosciences education was quite limited, he notes, but he found enough to get started. He began encouraging more discussion by providing students with handheld microphones, interspersing his lectures with short videos, and doing demonstrations in class to illustrate basic principles.

A further breakthrough in Yuretich’s thinking about instruction occurred when he served as a geology expert in a summer institute for K–12 teachers. As he worked with the teachers on developing hands-on learning activities, he kept thinking: “There’s nothing here that can’t work with undergrad students. So I started taking some of the things we were doing at the summer institutes and modifying them to work with the students in a lecture hall.” He incorporated activities into his lectures that students could do in their seats in small groups, such as graphing, conducting short experiments, and classifying fossils, and this “seemed to get things moving,” he says.

Yuretich and a group of colleagues received a National Science Foundation (NSF) grant to develop a systematic, campus-wide approach to improve science instruction for students who were preparing to become middle and high school teachers, and his oceanography class became the “test bed,” he explains. He and his colleague Mark Leckie designed a series of in-class exercises that students could carry out with their peers sitting next to them after a brief lecture by the
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instructor. The exercises are intended to “help students think like scientific investigators” (Yuretich et al., 2001). To better understand the principle of density, for example, students work together to answer these questions:

1. List some ways that you could measure the density of water.

2. Is salt water more or less dense than fresh water? How could you tell?

3. Design an experiment that would allow you to measure the change in the density of water as temperature changes.

Evidence collected over several semesters showed a marked increase in student attendance and exam scores, compared with previous classes, and a positive impact on students’ critical thinking skills as gauged by surveys and interviews (Yuretich, 2003). “Putting the toe in water is a better strategy than diving in and suddenly getting frozen,” says Yuretich. “We started out just doing a few trial things . . . and ultimately expanded to trying more,” he explains. “And then eventually the whole class changed over.”

In the decades since Mazur and Yuretich began seeking out information, evidence has grown about how students learn in science and engineering disciplines and which instructional strategies are most effective. And an array of resources—including faculty development opportunities, curriculum websites, networks of colleagues, and institutional supports—are available to help instructors apply these techniques and overcome challenges.

These research-based strategies can be adopted or adapted by instructors, and by those in positions to influence instruction, in all types of public or private higher education institutions: research universities, comprehensive universities, liberal arts colleges, other undergraduate institutions, or community colleges. They can work in various kinds of courses: introductory and upper-level courses, small and large classes, lectures and labs, and courses for majors and non-majors. And these strategies are feasible not only for instructors who are interested in doing formal studies of teaching and learning in their discipline, but also for anyone who is open to incorporating ideas from existing research and reflecting on their teaching practices in a systematic way.

As the following case study illustrates, that’s what Kaatje van der Hoeven Kraft did when she set out to improve her physical geology course at a community college with a large Hispanic enrollment.
In Kaatje Kraft’s geology classes at Mesa Community College in Arizona, the low-tech notebook is a tool for reflection—both for her students to reflect on what they are learning and for she herself to monitor students’ understanding and adjust her teaching accordingly.

**Investigating earthquakes using real data**

“Why do we get different magnitude earthquakes?” Kraft poses this question to her students near the beginning of one class period in physical geology.

The 24 students, a diverse group that includes many Hispanic students, offer a variety of answers: *The depth of the earthquake. How much the plates move. Tension.*

After nudging students to consider the elastic rebound theory, which they had just learned, Kraft directs them to talk with their tablemates about the factors that might generate different size earthquakes.

For the next few minutes, the students, who are seated at tables in groups of four, discuss this question. Several pause occasionally to write in colorful course notebooks filled with assignments, worksheets, questions for reflection, and their own notes and drawings. Kraft circulates among the students, listening to their conversations and asking probing questions. “Ooh, intriguing!” she exclaims in response to one student’s explanation.

Kraft moves to the front of the room, next to a large world map displaying the major plate boundaries. “Some of you are on the right track,” she says. “But some of you are thinking about intensity versus magnitude. It’s easy to confuse those.”

As students from each group report their possible explanations to the whole class, Kraft writes their responses on a whiteboard and summarizes: “The rate of plate motion might actually influence how often you get an earthquake, whereas how much energy is built up determines how big it is. And so we go back to the elastic rebound theory—the more stress you build up, the bigger the earthquake is going to be,” she says as she interlocks her fingers and pulls her hands in opposite directions until they release with a forceful jerk.

Kraft then preps students for the next task: each table of students will analyze one of six significant earthquakes that occurred between 2004 and 2011 in sites ranging from Chile to Sumatra. Each group will focus on four characteristics of their particular earthquake:

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*Except where noted, the information in this example comes from an interview with Kaatje Kraft, April 13, 2013, and from a video of Kraft teaching a geology class. At the time of the interview, Kraft was teaching at Mesa Community College in Arizona. She has since moved to Whatcom Community College in Bellingham, Washington (as of September 2014).*
1. Tectonic setting—whether the plate boundary is divergent (with plates moving away from each other) or convergent (with plates moving toward each other); and if it is convergent, whether it is a subduction zone, whereby one plate moves under the other and sinks into the Earth’s mantle, or a non-subduction zone.

2. Magnitude

3. Intensity at the epicenter and in other areas

4. Significant events such as loss of life, injury, or property destruction

Kraft encourages the students to consult data on the U.S. Geological Survey (USGS) website (every table has at least one laptop) and make sketches.

For the next 30 minutes, students talk animatedly. They look up information on the USGS website, consult their ubiquitous notebooks, and summarize what they found on small whiteboards. Kraft stops by each table to check on their progress and offer guidance. She tells them to write any remaining questions on a big whiteboard at the front of the room.

In the next segment of the class, students from each group present the highlights of their table’s investigation to the whole class. As the other students listen to these presentations, Kraft asks them to think about the commonalities and differences among the six earthquakes. Their ideas come into play during a final class discussion about the characteristics that tend to produce earthquakes of large magnitude and the factors that could lead to differences in intensity and damage for earthquakes of similar magnitude.

Later in the semester, at the end of the earthquake unit, students apply what they’ve learned to an earthquake “case study” that extends over four class periods (Kraft, n.d.). Working with real data, each group of students analyzes a particular aspect of a significant earthquake, such as the Alaska earthquake of 1964 or the San Francisco Loma Prieta earthquake of 1989. One group develops an overview, another analyzes the resulting tsunami, a third studies the geologic maps and intensity, and a fourth looks at the hazards incurred. Using the “jigsaw” technique described in Chapter 4, students from each group reassemble into new teams to share what they learned from their initial group’s analysis. These new teams come up with recommendations to government officials about the earthquake and its implications for future development, which they present to the whole class in a poster session. Next,

A group poster on a case study of the 1964 Alaska earthquake.
students write individual papers on the earthquake they studied, which are peer reviewed and revised. In a wrap-up activity, students reflect on their own strengths and weaknesses during the case study process and consider how they can be more successful learners in the future. This case study activity, which Kraft developed, has been rated as exemplary by On the Cutting Edge, a professional development program sponsored by the National Association of Geoscience Teachers.

**Becoming a reflective practitioner**

Kraft, who began teaching at Mesa in 1999, arrived at her current approach to teaching through what she describes as “a slow and gradual progression of learning more about the research and learning more about effective strategies.” Although her graduate school experience had piqued her interest in geology education, some of the interactive strategies she tried in her early years of teaching did not go so well. “But as a novice teacher, things sometimes generally don’t go so well. And as a novice teacher, I didn’t actually know that,” she explains. So she reverted to a more traditional way of teaching.

Her interest in trying new teaching strategies was rekindled in 2003, when she participated in a grant to develop curriculum in collaboration with middle and high school teachers. As a result of that experience, she began incorporating writing assignments into her courses in which students reflected on their learning. To expand her own knowledge of effective teaching strategies, she attended workshops offered by On the Cutting Edge. There she met faculty who were doing research on geology education. Kraft says the connections she made through these workshops have been “amazing” in helping her improve her teaching. “The more you have other people to bounce ideas off of and support you, the more likely you are to take risks and try things.” She has since led and presented at On the Cutting Edge workshops herself.

In 2007, Kraft took a sabbatical to collaborate on a project to study ways to improve student learning by engaging the affective domain—attitudes, motivation, beliefs, and other factors that can affect students’ behavior and performance (van der Hoeven Kraft et al., 2011). The sabbatical altered how she viewed her role as an instructor and her students’ roles as learners. “We really need to move away from that way of thinking that I just need to tell them everything I know. Rather, I have to help them negotiate content from the perspective of what I know,” she explains. Typical of a community
college, her students vary greatly in life experiences, prior preparation, and long-term goals, but most are taking an introductory geology course to meet a general science requirement. She wanted to teach in a way that would not only cover the required competencies, but also create an environment where students wanted to come to class and could develop skills that would serve them well no matter what they intended to pursue.

Reflecting on her own teaching has been an important part of her development as an instructor. “I started making notebooks, and I would reflect after every single lesson about what worked, what didn’t work, what would I like to change for the future semester, and how I would approach that particular topic. . . . Every semester was a revisionary process.”

**Using notebooks to encourage student reflection**

Student notebooks can be a valuable tool for encouraging students to “think about how they think,” writes Kraft (2012). Everything students do in her classes is placed in their notebooks, including handouts, quizzes, records of data and procedures, drawings of geological concepts, written work, and “reflections” they write before, during, and after an activity. “I essentially tell them they’re walking away having created their own personal textbook,” says Kraft, who assigns online readings but does not use a formal textbook. Students are required to complete the notebook as part of their course grade, “which means they have to come to class to submit their notebook—that helps assure attendance,” she explains.

Before class, students are required to do “reading reflections” in which they answer questions not only about the content of a reading assignment, but also about their prior knowledge and reaction to the reading. The reading reflection for a lesson on plate tectonics, for example, includes these questions:

- What were the main ideas from this reading?
- What questions do you still have from this reading?
- What surprised you most about this reading?

After each lesson, Kraft asks students to write down what they learned and how their ideas changed from their initial understanding. “So it’s helping them recognize that they come in with prior understanding and knowledge and that their learning can change . . . or that some things have just been reinforced,” she adds.

Periodically Kraft collects the notebooks; she grades students on whether they have completed the work and gives them feedback about their reflections. The information in the notebooks also helps Kraft reflect on her own teaching and modify her lessons to answer students’ questions and clarify concepts that are not well understood.

As part of the national Geoscience Affective Research NETwork (GARNET) project, Kraft is collecting data on her students’ attitudes and motivation. By the end of the semester, she reports, many students who initially felt they were “not very good at science” say they “love this science class.” She attributes that to her focus on concepts and student inquiry rather than terminology and memorization.
Kraft uses several research-based strategies that are described in Chapters 3 and 4 of this book. These include learning exercises that require students to participate actively during class, collaborative activities in which students can learn from each other, tasks explicitly intended to promote metacognition, or “thinking about thinking,” and opportunities for students to “practice” science using real data and tools of the discipline. And although community colleges do not generally require faculty to conduct research, a good way for faculty to maintain their scholarly practice is to participate in faculty development workshops, as Kraft has done. Her experience also shows the value of learning from the research of others, collaborating with a network of colleagues, and closely monitoring the impact of gradual changes in one’s teaching practice.

The Importance of Improving Instruction

The reasons for exploring more effective approaches to science and engineering education go beyond the personal. The actions that you, as an instructor or an influential leader, take—or do not take—to improve undergraduate teaching and learning have an impact on the nation’s future.

Consider, for example, the complex and worrisome challenges—new viruses, global climate change, nuclear terrorist threats, to list just a few—that will affect the quality of life for all of us, and for our children and grandchildren. Or consider the countless smaller decisions, from selecting health care to crafting food and land-use regulations, that citizens, consumers, parents, and political leaders make each day. Addressing these challenges and making these decisions will require a cadre of knowledgeable scientists and engineers and a scientifically literate public. College and university instructors and leaders play a critical role in preparing students to meet these challenges, whether as science and engineering professionals or as well-informed citizens.

In light of such challenges, instructors might ask themselves whether their courses are preparing science, technology, engineering, and mathematics (STEM) majors to solve new problems, communicate and collaborate effectively, and use their knowledge to contribute to society. Are their teaching approaches effectively helping students who are not headed toward a STEM career develop sufficient understanding of the “big ideas” of science and the ways of thinking about science to make good, rational choices?

During the past quarter-century, numerous national reports have emphasized
the need to improve undergraduate education in STEM fields as an essential step in preparing a diverse technical workforce and a scientifically literate citizenry.\footnote{These include Undergraduate Science, Mathematics, and Engineering Education, National Science Board (1986); Science for All Americans, American Association for the Advancement of Science (1989); Shaping the Future: New Expectations for Undergraduate Education in Science, Mathematics, Engineering, and Technology, National Science Foundation (1996); Transforming Undergraduate Education in Science, Mathematics, Engineering, and Technology, National Research Council (1999); and many others. A more complete list of major national reports calling for improvements in undergraduate science education can be found in Vision and Change in Undergraduate Biology Education: A Call to Action, American Association for the Advancement of Science (2011).} A 2012 report by the President’s Council of Advisors on Science and Technology (PCAST) warns that the United States is “putting its future at risk by forfeiting its historical strengths in STEM education” (p. 1). If the United States is to retain its edge, it will need to prepare roughly 1 million more STEM professionals during the next decade than would be produced at current rates, the report concludes. But too many students abandon STEM majors during their first two years of college, citing such reasons as “uninspiring introductory courses,” difficulty with the math required in introductory STEM courses, and an “unwelcoming atmosphere” from faculty who teach these courses (p. i). Increasing the retention rate of STEM majors from the current 40 percent to 50 percent would yield almost three-fourths of the 1 million additional STEM graduates needed during the next decade, the report estimates. (And even with such an increase, half of the students who start out pursuing a STEM major would not stick with it—still a disappointing attrition rate from most instructors’ perspective.)

Completion rates are significantly lower in STEM disciplines than in other majors for all student groups and are a particular concern for students from underrepresented racial and ethnic groups, who have lower college completion rates in general. For example, Hispanic and African American students are as likely to start college with an interest in science and engineering as white and Asian students, but they are less likely to persist (National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, 2011). Many of the reasons students give for switching out of a STEM major boil down to poor teaching in introductory courses (Seymour and Hewitt, 1997).

In light of these findings, you might ask: Is your style of teaching drawing students into science and engineering—or driving them away? Are you teaching in a way that motivates, engages, and supports the learning of all your students, including those with backgrounds or approaches to learning that differ from your own? Are your courses and your department’s programs serving as gateways to learning science or engineering, or gatekeepers?
Instructors of undergraduate science and engineering affect the future of our society in another important way—by helping to prepare prospective K–12 teachers. These future teachers will need a solid base of scientific knowledge and positive attitudes about science to foster understanding and interest in science among the children they will teach. They also need to experience effective instruction that actively engages students as a model for how they might teach later. Are your undergraduate science courses, especially those for non-majors, accomplishing these goals?

If your answers to any of the questions posed above are “maybe,” “I’m not sure,” or a candid “no,” then you may find ideas for energizing your instruction from an area of inquiry called discipline-based education research, or DBER, which emerged in the 1970s and has since gained momentum.

How Can DBER Help?

DBER combines the expertise of scientists and engineers about the challenges of learning a particular discipline with broader theories about teaching and learning. DBER investigates learning and teaching in a discipline using a range of methods with deep grounding in that discipline’s priorities, worldview, knowledge, and practices. It is informed by and complementary to more general research on human learning and cognition. DBER also helps to identify appropriate methods for investigating the learning and teaching processes. Thus, DBER scholarship has the practical goal of improving science and engineering education for all students.

DBER has generated insights that can be used to improve science and engineering education for all students. In particular, DBER sheds light on how students learn concepts and ways of thinking in a discipline and which types of teaching strategies can help students learn more effectively and retain what they have learned.

The major findings from peer-reviewed DBER studies, as well as the status of DBER as a research enterprise, are synthesized in a 2012 report by the National Research Council (NRC), Discipline-Based
Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering. This NRC report is the source of much of the information in this book and includes a wealth of additional material for those who want to explore the research base in greater depth.

Theories of learning as a basis for instruction

The purpose of instruction is to help students learn. DBER starts from the premise that a more complete and nuanced understanding of how people learn science and engineering can lead to better instruction.

As described in Chapter 3, many findings about learning from DBER are heavily influenced by theories from cognitive research, which hold that learning involves much more than simply acquiring factual knowledge. Rather, students generate their own understandings and form meaning as a result of their experiences and ideas. Students’ prior knowledge, including their mental models and pre-conceptions, may hinder or promote learning. Some DBER studies also draw from research on sociocultural theories of learning, which shows that students enrich their understanding by interacting with others who share a common interest.

DBER studies further reveal that undergraduates, as novices, have misunderstandings about a wide range of fundamental concepts in science and engineering. Such misunderstandings are common and even normal as many scientific explanations of the world run counter to our intuitive beliefs about how the world works (for example, the idea that everything around us—even a solid table—is made of tiny, moving particles can be tough to grasp at first). They also have difficulty mastering aspects of these disciplines that may seem easy or obvious to experts, such as solving problems or understanding graphs, models, and other visual and mathematical ways of representing important ideas.

These common student difficulties pose challenges to learning. Well-designed instruction recognizes and confronts these difficulties. It activates ways of thinking that can help novices integrate or replace their prior knowledge with new information to construct more expert-like understanding.

Evidence from DBER about student-centered instruction

Many DBER studies have looked at the effectiveness of “student-centered” instructional approaches, in which learners build their understanding by applying the methods and principles of a discipline and interacting with each other under the guidance of the instructor. Student-centered instruction can take a variety of forms,
Studies clearly show that student-centered instructional strategies are more effective in improving students’ conceptual understanding, knowledge retention, and attitudes about learning in a discipline than traditional lecture-based methods that do not include student participation.

As described in more detail in Chapters 3 and 4. Common elements often include actively engaging students in meaningful individual or group tasks, conducting frequent formative assessment, and encouraging students to think about and articulate their own understanding and reasoning, among others. Often DBER studies compare the effectiveness of a student-centered approach with the more traditional mode of an instructor transmitting factual information to a passive audience of students, predominantly through lectures.

In general, DBER scholarship and related studies clearly show that student-centered instructional strategies are more effective in improving students’ conceptual understanding, knowledge retention, and attitudes about learning in a discipline than traditional lecture-based methods that do not include student participation. A limited amount of research suggests that making even incremental changes toward more student-centered approaches can enhance students’ learning.  

The following excerpts from literature reviews, including several commissioned by the NRC to inform its DBER study, highlight the positive impacts of student-centered instruction in specific disciplines:

- In physics, results from conceptual and problem-solving tests administered to thousands of students “strongly suggest that the classroom use of [interactive engagement] methods can increase course effectiveness well beyond that obtained in traditional practice” (Hake, 1998, p. 1).

- Studies of chemistry education during the past decade demonstrate that various forms of socially mediated learning (in which students create meaning through interactions with others) produce positive outcomes, including “significantly higher test scores, higher final grades, better conceptual understanding, lower course withdrawal rates, and positive impacts on attitudes” (Towns and Kraft, 2011, p. 7).

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4 For a summary of this research and references to key studies, see Chapter 3 of this book. A more complete list of relevant studies can be found in Chapter 6 of the 2012 NRC report on DBER in the Overview section and the section on Instruction in the Classroom Setting.
• In engineering, actively engaging students “can be unquestionably confirmed as the best learning situation for learning the skills of both problem analysis and engineering design. It is also the most widely demonstrated key to deep conceptual understanding” (Svinicki, 2011, p. 15).

• Frequent assessment in combination with active student engagement has been shown to significantly improve student performance in biology. In addition, several analyses have shown that collaborative learning, particularly collaborative testing, improves student retention of content knowledge in biology (Dirks, 2011).

• To produce significant gains in learning in geosciences, “it is necessary to use instructional strategies that minimize lecture and maximize other teaching methods. We know that students learn best when they are engaged with real objects or phenomena, working in cooperative groups, solving complex problems, and interested in what they are learning” (Piburn, Kraft, and Pacheco, 2011, p. 19).

This is not how most faculty members teach undergraduate science and engineering. Traditional lecture is still the most common mode of instruction. Science and engineering faculty are more likely, on average, to rely primarily on lectures than instructors in other fields and are the least likely to use student-centered or collaborative instruction (Fairweather, 2005; Schuster and Finkelstein, 2006).
A scientific or engineering mindset

Applying findings from research on teaching and learning to improve your instruction involves the same type of thinking you would use to solve a scientific or an engineering problem in your discipline, whether it is studying how fungi adapt to cold temperatures or developing new construction materials from industrial waste. Jo Handelsman, a Yale University biology professor, uses the phrase “scientific teaching” to refer to the process “in which teaching is approached with the same rigor as science at its best” (Handelsman et al., 2004, pp. 521–522).

Paula Heron, a physics professor and education scholar at the University of Washington, describes it as “both brilliant and obvious to take the perspective of an experimental scientist and apply it to teaching and learning in the discipline.”

Others see similarities between instructional redesign and engineering design, in that both seek to improve complex systems (such as human learning) within the constraints of available resources. In both endeavors, write Purdue University engineering professors Ruth Streveler, Karl Smith, and Mary Pilotte (2012), “we start with requirements or specifications, emphasize metrics, and then prepare prototypes that meet the requirements” (p. 1).

In 2003, Beth Simon was in her second year as a professor in computer science at the University of San Diego when she “began to think about my teaching with the same sort of brain that I use in doing my computer science research,” she says. “My previous computer science research was in optimization, which is about making computer programs go faster. So I would always wonder, where are the inefficient parts?” When she would create a new lecture, she would wonder, “Did that go better than the old one? How would I know? How would I measure it? How can I figure out if I’m producing a better, more efficient, and optimal learning experience for students?”

This insight led Simon on a quest to learn more about effective instructional practices. She participated in a three-year NSF-funded project where she learned how to do qualitative research on instruction. She later took a sabbatical to become a Science Teaching and Learning Fellow in the Carl Wieman Science Education Initiative at the University of British Columbia. When she took a teaching position at the University of California, San Diego (UCSD), she implemented Mazur’s Peer Instruction approach in her courses as a means to improve students’ learning and retention and to attract more women and students from...
underrepresented groups to the computer science major. Simon has since collaborated with faculty at other institutions to study the impact of more interactive approaches to teaching computer science. Their research shows a dramatic decrease in failure rates among students taught with Peer Instruction (Porter, Bailey-Lee, and Simon, 2013). In her current role as senior associate director of UCSD’s Center for Teaching Development, Simon continues to apply a researcher’s mindset to improving instructional practice across the computer science and engineering department.

**Does This Mean the End of Lecturing?**

Findings from DBER and related research do not mean that lecturing is inherently ineffective and should be eliminated. Lectures can be student-centered if they are carefully crafted to consider student needs, background, and understanding and are implemented with opportunities for student responses. Nor do these findings mean that student-centered approaches are automatically more effective. Good instruction involves more than just asking students questions or putting them to work on activities; it also means helping to move students toward the types of expert thinking that characterize the knowledge and practices of a discipline. The point is that any instructional approach should be used in a thoughtful way that promotes student learning.

Research has identified a variety of instructional strategies that can enhance student learning, including several discussed in more detail in Chapter 4. These strategies range in scope and complexity from increasing student interaction within a basic lecture format to devoting the bulk of class time to activities in which students work together to solve complex problems.

Peer-Led Team Learning (PLTL) is an example of a research-based approach that requires only modest changes in a lecture course and can be implemented with materials developed by others. As explained in the following case study of the PLTL model developed by David Gosser at the City College of New York, a portion of a lecture course is replaced with a workshop, led by trained undergraduates, in which students collaborate in small groups to solve problems or complete other exercises that reinforce the concepts taught in the lecture.
In 1990, David Gosser was a junior faculty member in the chemistry department at the City College of New York (CCNY), an institution he describes as “basically the UN [United Nations]” in terms of student diversity. The department had a problem with student attrition. The general chemistry introductory course enrolled several hundred students, including many who did not plan to major in the subject. Just 45 percent received a passing grade.

To tackle this problem, Gosser investigated a model that had been used successfully by Uri Treisman at the University of California, Berkeley, in which students reinforced what they were learning in lectures by working on problems in study groups led by graduate students. At CCNY, however, hundreds of students took General Chemistry, and the graduate student population was too small to provide a sufficient number of peer leaders for the study groups; about 12 such leaders would be needed every semester for each section of 100 General Chemistry students. Therefore, CCNY recruited undergraduate students who had done well in chemistry in the first semester to serve as “peer facilitators” in the second semester, explains Gosser.
who currently directs the Center for Peer-Led Team Learning at CCNY. One hour of a four-hour lecture course was replaced with a weekly two-hour workshop. The class was divided into numerous workshop sections of six to eight students, each led by a peer facilitator.

“Even starting from a simple idea and using off-the-shelf problems, [the model] was very robust,” says Gosser. “It was clear that students enjoyed the structure.” Gosser received a National Science Foundation grant that provided a major stimulus for the program and met with faculty from his college’s School of Education to incorporate research on collaborative learning.

A critical component of this model, called Peer-Led Team Learning (PLTL), is the training provided to peer facilitators, who are paid a stipend. At CCNY, these students participate in an orientation session before the semester starts, are overseen by a faculty member throughout the semester, and attend weekly meetings to practice and discuss the material they will cover that week. Faculty make an effort to ensure that the problems studied in the peer-led sessions are well matched to the topics covered in the lecture.

In the training sessions, facilitators practice strategies to elicit students’ reasoning, says Roland Maio, who was a peer facilitator in spring 2013. “You want [the students in your section] to work through the problem. You don’t want them to just sit there if they’re stuck, but you don’t want to throw the answer at them. That sort of teaching style is part of PLTL,” he says. When most of the students seem unsure about how to approach a problem, “then I fall back on a Socratic method, asking questions to bring out their own reasoning and see what they are thinking.”

In the peer-led sessions, students collaborate on problems that are slightly more difficult than standard end-of-chapter textbook questions. Often these problems require students to record their observations and carefully outline the logic used to arrive at a solution. For example, one such problem asks students to draw the structure of several molecules and determine the molecular geometry of each structure. In another problem, students simulate chemical reactions using pennies, nickels, and dimes and discuss their conclusions before writing out formulas. Manipulating objects helps students understand the role of particles, Gosser explains, a concept that is not obvious by simply learning a formula.

The workshop sessions can be particularly empowering for introverted students, says Ashea West, who served as a peer facilitator in spring 2013. “You can be intimidated by professors in a big lecture hall with big classes. Students who are really shy and not outspoken were better after the workshop. It is an easier way for students to learn more and make friends for study groups.”

One barrier to many reform models is that they require faculty to “turn upside down their whole approach,” says Gosser. “With PLTL, the faculty have a much bigger comfort zone because they can start from where they are. . . . It’s a lot less disruptive to their approach. You can still lecture pretty much the way you want, but you have to think about integrating it with this workshop.”

The PLTL model has been widely replicated in science and engineering disciplines at more than 100 sites nationally, and a large number of appropriate PLTL problems are readily available for instructors who want to try this approach. A review of studies of PLTL at several institutions found a higher percentage of A, B, or C grades and higher test performance among students participating in PLTL workshops compared with nonparticipants (Gosser, 2011).

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b Interview, August 13, 2013.

c Interview, August 14, 2013.
PLTL illustrates how strategies of collaborative learning and problem solving can be imported into a large lecture course. The small-group sessions provide students with extra exercises to help them master difficult concepts, as well as additional opportunities to receive answers to their questions. These sessions also engender a sense of community and encourage students to learn from each other and take responsibility for their own learning. Students gain experience with working in teams and communicating better, while peer leaders hone their teaching and group management skills and strengthen their self-confidence.

**Scaling Up Research-Based Instruction**

So if research-based instruction works, why aren’t more people doing it?

Handelsman and her colleagues (2004) put this question another way: “So why do outstanding scientists who demand rigorous proof for scientific assertions in their research continue to use and, indeed, defend on the basis of their intuition alone, teaching methods that are not the most effective?” (p. 521).

Efforts to encourage undergraduate STEM faculty to adopt research-based teaching approaches are often beset by challenges. For example, in a national survey of physics faculty, Henderson, Dancy, and Niewiadomska-Bugaj (2012) found that nearly all faculty were familiar with one or more research-based practices, and approximately half were using at least one such practice. At the same time, however, many faculty had modified the research-based practices, and they frequently discontinued a practice after trying it for one semester. The researchers surmised that faculty who abandon research-based practices either lack the knowledge needed to customize the practice to their local situation or underestimate the other factors that tend to discourage innovation in teaching.

Rogers’ (2003) seminal theory of the diffusion of innovation proposes that the decision to adopt and sustain an innovation begins only when an individual has knowledge or awareness of the innovation. The next step is persuasion, as the individual evaluates the innovation, a process strongly influenced by the views of close peers. If the individual decides to adopt the innovation, possibly with some modifications, he or she often remains uncertain of its benefits. The final step is confirmation, when the individual looks for support for his or her decision. At this stage, the individual may decide to discontinue the innovation.

Instructors who are resistant to or skeptical about adopting research-based teaching strategies often emphasize practical challenges. For example, they may
Good instruction involves more than just asking students questions or putting them to work on activities; it also means helping to move students toward the types of expert thinking that characterize the knowledge and practices of a discipline. The point is that any instructional approach should be used in a thoughtful way that promotes student learning.

effect concerns about possible negative reactions from students accustomed to traditional types of teaching, the time involved in redesigning a course, the challenge of learning new teaching methods, the feasibility of supporting active student engagement in a large lecture hall, or the need to drop important content to make time for student interaction.

Other research on factors that influence faculty decisions about teaching practices points to challenges in the areas of institutional leadership, departmental peers, tenure and reward systems, and the beliefs and values of the individual faculty members themselves (Austin, 2011; Fairweather, 2008). These challenges, along with ways to surmount them, are discussed in Chapters 6 and 7.

While you may cringe at the prospect of having to dramatically revamp an entire course all at once, you may be heartened to know that most effective instructors did not attempt such a feat. Even instructors who have thoroughly embraced student-centered instruction, like Scott Freeman at the University of Washington, often started with modest changes. In his early years of teaching introductory biology, Freeman mostly lectured. But as he became more familiar with the research on science instruction, he added more and more strategies to actively engage students and began collaborating with colleagues to study the impact of these changes. Eventually, as the following case study shows, Freeman did away with formal lectures, even as enrollments soared to several hundred students. Instead he structures his course around “clicker” questions that students answer anonymously using handheld devices and group exercises that probe students’ understanding of biology concepts. The closest he comes to lecturing is when he introduces an activity, answers a question that could benefit the whole class, or clarifies a confusing point.
Scott Freeman cues up his slides, adjusts his remote mic, and walks casually to center stage of the largest lecture hall at the University of Washington. Most of the auditorium’s 700 seats are filled with students talking, laughing, and flipping through notebooks. This scene could be the prelude to any traditional lecture at any large university. But as the class unfolds, it becomes clear that the Biology 180 course taught by Freeman is far from traditional.

In this highly structured course, students are responsible for learning basic information on their own time through assigned readings, daily online quizzes, and weekly practice exams. This frees up class time for active learning exercises that challenge students to apply concepts, analyze data, and reflect on their reasoning with expert guidance and feedback from the instructor. But the course, which focuses on evolution, Mendelian genetics, and ecology, did not start out this way. Rather, it evolved, so to speak, as Freeman gradually introduced research-based instructional strategies and as he and his colleagues studied the year-by-year impact of these changes on student performance.

Clicker questions challenge students’ thinking

“Clickers out, cellphones off,” says Freeman, signaling the official start of the 50-minute class. Several students fiddle with their clickers—handheld response devices that resemble small TV remotes. “In our last adventure yesterday,” Freeman begins, “you were figuring out that inbreeding and other forms of nonrandom mating are going to increase the percentage of homozygotes in a population. So it’s clicker time—think about this one please.” The large screen at the back of the stage displays this clicker question, which is based on the previous day’s reading assignment:

Q: Why do small populations become inbred?

1. They are usually stable or declining in size.
2. Population bottlenecks cause large changes in allele frequencies.
3. Founder events establish small populations in isolated habitats (low likelihood of gene flow, after the founder event).
4. Eventually, all individuals are closely related.

* Except where noted, the information in this case study comes from an interview with Scott Freeman, May 24, 2013, and from an unpublished video of Freeman teaching a class provided by L. Tong and P. Liggit, Eastern Michigan University.
The students have less than one minute to consider the question individually and record their initial responses with the clickers. “Ten more seconds . . . five seconds,” says Freeman. “Okay, start talking it over, please.”

The room fills with chatter as students turn to their neighbors to discuss their answers and the reasoning behind them. Freeman chooses clicker questions that are difficult enough to stimulate students’ thinking and include common student misconceptions among the possible answers. “You’re shooting for student responses of 40 to 60 percent [correct] the first time they look at the question,” he says in a later interview, adding that it is important to use clickers in ways supported by evidence. “There’s a tremendous amount of clicker abuse going on,” he asserts, citing the example of instructors who use clicker questions that are too easy. “We have tons of people saying, ‘Oh, yeah, I do active learning; I use clickers.’ And they’re seeing no changes in student responses because they’re not using them right.”

After a few minutes, Freeman closes out the peer discussion and asks for volunteers to share their answer with the whole class. “Remember to explain your logic,” he reminds them. A student in the middle of the auditorium confidently lays out her reasons for choosing answer 4. Two more students chime in with additional arguments on behalf of choice 4.

“Actually, a lot of people answered 3,” says Freeman. “So you think 4 is a true statement. Then you have to parse: first, is it true, and then, is it addressing the issue you’re raising now? Is it causative—would that be a mechanism why small populations become inbred?”

The discussion continues for a few more minutes, as more students explain why they think a particular answer is correct. Freeman asks for a show of hands from the students who agree that 4 is the correct answer. Hundreds of hands shoot up. Next a smaller number of students raise their hands to indicate they disagree. “The correct answer is 4,” Freeman reveals, adding that students who are still uncertain or have questions can see him during office hours, email him, or talk more about this topic during an exam review session scheduled for the next day.

For the next 15 minutes, the students work through three more clicker questions using the same
model of thinking and responding individually, talking with their neighbors, and discussing responses with the whole class. At this point, however, Freeman switches to “randomized calling”—using a randomly generated class roster to pick which students will explain their answers. (Students have the option of passing or putting themselves on a “do not call” list.) Randomized calling helps ensure that students are prepared for class, Freeman later explains. In one end-of-course evaluation, he asked students what they thought of this approach to calling on students: “the overwhelming majority said they absolutely hated it—but make sure you do it all the time.”

From lecture to highly structured active learning

“What motivated me was failure,” says Freeman about the evolution of his introductory biology course. When he first started teaching the course in 2001, he used a modified Socratic style in which he mostly lectured but stopped occasionally to ask questions of students. But he soon became discouraged by the high percentage of students who dropped the class or received a final grade of less than 1.5 on a 4.0 scale. (More than 18 percent of students fell into this latter category in spring 2002, which meant they could not advance to the 200-level biology course.) About 40 percent of all University of Washington undergraduates take Biology 180, mostly as sophomores, and the five-credit course is a prerequisite for biology majors. The class meets four times a week, plus a two-hour lab session.

To address the failure rate and improve student learning, Freeman reviewed the developing research literature on active learning and attended a National Science Foundation workshop with some of his colleagues. He also began collecting data on his own class. “I wanted to convince myself, and eventually my colleagues, that if I changed what I was doing in my classroom and saw changes in student performance, I could actually have the data to show that something real was going on.”

Spurred by research suggesting that active learning can help reduce student failure rates without compromising the rigor of a course, Freeman began to incorporate more active strategies into his teaching. In 2003, he added ungraded active learning exercises to his Socratic lectures. These included Think-Pair-Share activities (see Chapter 4) in which students individually consider a question posed by the instructor, discuss their ideas with a neighbor, and arrive at a final answer, which is then discussed by the whole class. These ungraded additions didn’t work very well, says Freeman. “I didn’t see any change in student performance.”

Starting in 2005, when technology made it practical to use clickers in a large class, Freeman made time during his lectures for daily clicker questions with peer discussion. (A grant from the university provost paid for the initial purchase of the clicker technology.) He also added online weekly practice exams consisting of five short-answer questions that were graded by peers. As he had done in the past, he gave two midterm exams and a final. As different strategies were tried in the course, Freeman and his colleagues David Haak and Mary Pat Wenderoth documented the impact. With the addition of clicker questions, the percentage of students who received failing final grades decreased (Freeman et al., 2011).

In fall 2007, Freeman stopped giving formal lectures altogether—an approach he has maintained even as enrollments soared from 340 to a high of 700 in 2009. He began using clicker questions and worksheet problems to drive the entire discussion of a given topic, and he introduced randomized calling and daily quizzes on reading assignments in addition to the practice exams. “Essentially, I
was flipping the classroom,” he says, referring to a model in which students learn basic information outside of class and work on collaborative projects and problems during class time that are designed to deepen their understanding. “If the students have done the reading, they have the basic information to be prepared to work on problems before they come to class.” He still gives what might be called mini-lectures in class, but primarily to answer questions, guide the discussion, or provide a brief introduction to worksheet problems.

The active learning elements “made the class size of 500 seem a bit smaller,” says Hyunsoo Bak, who took the class as a sophomore in fall 2012. “It was fun.” In her view, the main benefit of the class was that “it put more weight on how I think . . . and why I think that way.”

The class redesign did not require more money, smaller class sizes, or more class time (Haak et al., 2011). In fact, during the period studied (2002–2009), class size increased, the number of graduate teaching assistants decreased, and the hours devoted to labs were reduced.

**Group worksheets elicit students’ understanding**

Students in the Biology 180 class also collaborate on longer worksheet problems. Some of these problems are intended to “show students that their intuition doesn’t work and get them to start thinking about the problem,” says Freeman. Others are

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\(^{b}\) Interview, June 28, 2013.
designed to confront common student misconceptions in biology, such as the notion that genetic mutations arise in response to the environment rather than randomly.

One such worksheet asks students to create a section of a “tree-of-life” diagram showing the evolutionary relationships among six groups of animals: lizards, ray-finned fish, mammals, snakes, amphibians, and sharks and rays. To set up this activity, Freeman provides a two-minute explanation of the role and history of these phylogenetic trees. Working in groups of three for about 20 minutes, students create their trees, using a data table that shows whether a specific group has a particular trait, such as internal bones, limbs, and amniotic eggs. To get students thinking about traits that distinguish one species as an outgrowth of another, Freeman sings a snippet from an old Sesame Street song: “One of these things is not like the other!”

As the students work, Freeman and his teaching assistants circulate among the groups, monitoring students’ discussions and using questions to subtly guide those who seem confused. Often he stops to praise a student for a correct answer or a useful contribution to the group’s discussion.

Kaitlyn Lestak, a biology major, recalls in a later interview that when she was stumped by something in the worksheets, Freeman “wouldn’t really give you the answer to any question, but he would talk you through it in a way that could help you solve it. Or he would ask, ‘What do you think the answer is?’ And you would give him your answer, and he would say, ‘You’re on the right track, but think about this instead.’ He would ask you questions to help you get the right answer eventually.” Although the course was challenging, says Lestak, she believes the level of challenge helped her to learn. “I’ve never taken a class so engaging.”

Evidence of effectiveness

From 2003, when Freeman began revamping the Biology 180 course, to 2009, when he had fully implemented the highly structured version, the percentage of students who received failing final grades decreased from 18 percent to 6 percent (Freeman et al., 2011). Freeman and his colleagues did special analyses to control for student ability and ensure that the test questions had not become easier. They concluded that the class itself was consistent, if not slightly more difficult, across the years of the study.

Particularly encouraging was the disproportionate drop in the failure rate for students from educationally or economically disadvantaged backgrounds (Haak et al., 2011). (About 45 percent of students enrolled in the course are Asian American, about 45 percent are white, and roughly 10 percent to 12 percent are from minority groups underrepresented in science; altogether, about 15 percent of the students are from disadvantaged backgrounds.) The researchers attribute these improvements in performance to the many opportunities students have in class to apply scientific thinking by solving problems, reflecting on and articulating their reasoning, and considering other points of view.

To his colleagues who resist using evidence to change their teaching, Freeman points out that they would readily adapt a powerful new technology that makes it easier for them to do biological research. “If they just brought that same mindset to their teaching, I think things would change in a hurry.”

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6 Interview, June 27, 2013.
Freeman’s experience addresses some common concerns about the feasibility of implementing research-based strategies and contains guidance for others who are interested in trying similar approaches:

• The evolution of Freeman’s Biology 180 course illustrates how an energetic instructor with a strong commitment to improving student learning can introduce active learning strategies—and revise, discontinue, or add to these strategies based on classroom data about their impact.

• The later, more highly structured version of the course shifts more responsibility to the students to learn basic content and vocabulary outside of class through assigned reading, quizzes, and practice exams. This partly addresses a common concern among instructors that if they increase student interaction, they will not be able to cover important content. Just because content is covered does not mean students will learn it.

• Even in a class of up to 700 students taught in a traditional lecture hall, it is possible to reduce lectures to a minimum and shift the instructor’s role from delivering information to guiding student learning. Rather than directly telling students who are stuck on a problem what to do, the instructor asks probing questions that nudge students to think in a different direction.

• Simply injecting clicker questions into a lecture does not mean an instructor is implementing a research-based practice. As discussed at more length in Chapter 5, it matters a great deal whether the questions are appropriate in their level of difficulty, address common student misconceptions, are nested within a larger research-based course design, and, most importantly, are presented in a format that allows students to discuss their ideas with their peers.

**Conclusion**

The ideas and examples described in this book are not meant to be a “bag of tricks” from which you can whip out a slick activity for tomorrow’s chemistry class. Rather, they are intended to encourage you to reflect on your teaching and consider trying new approaches that are compatible with the learning goals for your course.

Many instructors who have gone down this path not only say it was worth the effort, but also declare they can no longer imagine teaching any other way.
Their students are more enthusiastic and motivated and have better attendance. Often their students have higher performance as a group than those in their previous classes or in traditionally taught sections of the same course. Through activities that encourage student reflection and various forms of assessment, instructors can better grasp how well their students understand fundamental concepts.

Although students may balk at first when they are asked to assume greater responsibility for their learning, they often become enthusiastic supporters of active learning strategies. According to Karen Kortz,7 a geology professor at the Community College of Rhode Island, many of her students tell her, “I love this class; it makes me feel like I’m not afraid of science.” She elaborates: “One of my goals is to have students enjoy the class. I don’t mean make it easy for them. I mean make it so they’re not afraid of it, and they like attending and doing the work.”

Changing your teaching can also be rewarding and intellectually stimulating for you as an instructor. Beth Simon8 at the University of California, San Diego, tells the story of a colleague in the computer science and engineering department who adopted some of Simon’s Peer Instruction materials. Midway through the term, Simon asked the colleague how the course was going. “He said, ‘I haven’t had so much fun teaching in a long time. This is why I wanted to go into education. I didn’t want to stand up and talk at students. I wanted to have interesting discussions with them.’” Simon adds: “And that’s something we’ve seen frequently.”

### Resources and Further Reading

Center for Peer-Led Team Learning
https://sites.google.com/site/quickpltl

Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering (National Research Council, 2012)
Chapter 2: The Emergence and Current State of Discipline-Based Education Research

Engage to Excel: Producing One Million Additional College Graduates with Degrees in Science, Technology, Engineering, and Mathematics. Report of the President’s Council of Advisors on Science and Technology (February 2012)

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7 Interview, April 5, 2013.
8 Interview, August 20, 2013.