REFUELING THE U.S. INNOVATION ECONOMY:

Fresh Approaches to Science, Technology, Engineering and Mathematics (STEM) Education

by Robert D. Atkinson and Merrilea Mayo

ITIF
The Information Technology
& Innovation Foundation

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ABOUT ITIF

The Information Technology and Innovation Foundation (ITIF) is a Washington, D.C.-based think tank at the cutting edge of designing innovation policies and exploring how advances in information technology will create new economic opportunities to improve the quality of life. Nonprofit, and nonpartisan, ITIF offers pragmatic ideas that break free of economic philosophies born in eras long before the first punch card computer and well before the rise of modern China. ITIF, founded in 2006, is dedicated to conceiving and promoting new ways of thinking about technology-driven productivity, competitiveness, and globalization for the 21st century.

ITIF publishes policy reports, holds forums and policy debates, advises elected officials and their staff, and provides an active resource for the media. It develops new and creative policy proposals, analyzes existing policy issues through the lens of bolstering innovation and productivity, and advocates against policies that hinder digital transformation and innovation. The Information Technology and Innovation Foundation is a 501(c)3 nonprofit organization.

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TABLE OF CONTENTS

CHAPTER 1:

Time for a New Approach to STEM Education

Students at Olin College of Engineering in Needham, Massachusetts.

For over a half century, science-based innovation has powered America's economy, creating good jobs, a high standard of living, and U.S. economic and political leadership. Yet, our nation's global share of activity in STEM-focused industries is in decline, jeopardizing our status as the world's leader in innovation.[1] Moreover, there is clear evidence that the United States is consistently not able to produce enough of its own STEM workers in key fields (e.g., computer science, electrical engineering), even though the best universities for studying these subjects are U.S.-based. While increasing the quantity and quality of U.S. STEM graduates will not by itself solve the problem of declining U.S. innovation-based competitiveness, it is an important component of a larger national innovation strategy. Consequently, there is increasing concern over how to give more American students stronger STEM skills and get them into STEM jobs.

While a few science and technology policy experts might dispute this framing, most embrace it. In fact, the last 30 years has seen a widespread consensus that America needs to do a better job at promoting and supporting STEM education. Indeed, numerous task forces, commissions and study groups have produced an array of reports and calls to action (see Box 1.1). The general consensus regarding the nature of the problem, its causes and needed solutions has led some policy makers to proclaim that the last thing we need is another report. We know what to do, so goes the refrain. After all, previous reports have provided a detailed road map. Now is the time for action. According to this line of thinking, we have good ideas, but lack political will. Too few citizens and policy makers recognize the importance of the problem and the critical need for solutions.

Indeed, it's hard to imagine what more could be done to direct attention to the importance of the problem. Yet little seems to change, despite the continued proliferation of reports to Congress raising the same alarm, identifying the same problems, and calling out for largely the same solutions.

Certainly, it would be better if Congress and federal Administrations had devoted more attention to this problem. But some action has been taken. Congress has passed numerous pieces of legislation over the years to address STEM education and Administrations, including the current one, have established new STEM initiatives. So perhaps the problem is not a lack of political will in Washington and state capitols, but a lack of the right approach to the problem. This report argues that the prevailing approaches to solving the STEM challenge that are so widely agreed upon in Washington are in fact quite limited and that what are needed are fresh approaches that drive innovation in STEM education, so that we can drive innovation and jobs in the U.S. economy.

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LIMITATIONS OF THE CURRENT "SOME STEM FOR ALL" APPROACH TO STEM POLICY

Virtually every report and call to action on STEM education is based on what could be called a "Some STEM for All" approach. In other words, the prevailing view is that the way to ensure that more Americans have needed STEM skills is to make sure that along every step of the way, from K to 8, to high school, to college and to graduate school all students get as much and as high a quality STEM education as possible. Interventions grounded in this approach include boosting K–12 STEM teacher quality (e.g., increasing teacher pay, requiring higher STEM teacher qualifications), imposing more rigorous STEM standards (e.g., expanding requirements for STEM courses, more testing and assessment), improving curriculum (including further studies of the most effective STEM pedagogies and learning materials), and boosting awareness among students of the importance and attractiveness of STEM careers. In other words, STEM is so important that we can't afford not to have every student in America given the best STEM education, with the hope that this will increase the likelihood that at least some of them will go into STEM jobs. Moreover, the thinking goes, because STEM jobs pay more and are growing faster than other occupations our education system should produce more STEM grads who can take advantage of these rewarding employment opportunities.

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The logic in such an approach is intuitively appealing and powerful, which is why virtually every STEM report has embraced it as a given and structured its recommendations around it. If we want more STEM grads, why shouldn't we create as many candidates as possible—by promoting "STEM for All?" However, this report identifies five overriding characteristics of the current approaches to STEM policy that limit progress toward the goal of—getting more American workers into STEM jobs and in so doing, expanding STEM jobs and economic activity even further.

Improving STEM is a not Linear, Mechanistic Process

First, the "Some STEM for All" solution is grounded in what can best be termed the "mechanistic model" of public policy intervention. In the mechanistic model, the path from A to B is a straight line, best achieved by taking steps like creating and funding a program (e.g., expanding teacher salaries) or creating and enforcing standards to make something happen (e.g., requiring teachers to have degrees in field of teaching). In this view, for example, if we want more STEM students, then we should create and fund a program to train teachers. As we will argue below, the "complexity view" of public policy intervention suggests that the production and demand for STEM talent are not simple, mechanistic systems such that pouring more resources in at the front end automatically leads to more and better results. Rather, they are complex systems with multiple actors, motivations, feedback loops, uncertainties, and a host of other complex factors. Thus, simple and "obvious" solutions are not always the right ones. In part for this reason, the strategies based on the "Some STEM for All" approach are not likely to be the most effective at producing more and better STEM graduates. As we discuss in Chapter 4, research suggests that many of the policy interventions emerging from this paradigm are actually not very effective. Instead, we need to create new kinds of STEM educational institutions and curricula.

Giving All Students Some STEM is Expensive

Second, this approach does not recognize that while STEM is critical to the economy, very few workers actually need extensive STEM skills. In fact, STEM jobs constitute at most 5 percent of all jobs.[2] The vast majority of American workers are not scientists, technologists, engineers, or mathematicians. Yet the "Some STEM for All" approach would ensure that all students, even those who would never become a scientist or engineer regardless of how good their teachers are or how high paid the career is, have the best STEM education that money can buy. But, to make a musical analogy, while music is important to society, not everyone needs to know how to play a musical instrument, and it would be a waste of societal resources to invest large amounts of money to ensure that every student has access to a Steinway piano and Juilliard-trained music teachers. Implementing a "Some STEM for All" approach requires a much larger expenditure of societal resources than the more targeted "All STEM for Some" approach discussed below. We advocate more reliance on lower cost tools such as better information on how institutions perform to drive improvement, and more partnerships with industry to promote STEM.

More Money Won't Solve the Problem

A third major limitation of the prevailing approach to STEM policy is that it is based on the idea that our educational institutions are not performing adequately because of a lack of resources or knowledge about the best way to structure STEM education, as opposed to a lack of motivation, creativity or flexibility. To continue the musical analogy, if we just increased funding, bought more Steinways and hired more Juilliard-trained teachers we'd go a long way toward solving the problem.

Likewise, if we just funded more research on the best ways to teach STEM and then communicated that to every middle school, high school, college and university in the country, we'd transform STEM education. According to the prevailing view, schools at all levels don't do a better job because they are not aware of the best curriculum and pedagogy or because best practices have yet to be identified. Virtually all STEM reports urge educational institutions to "do the right thing" (e.g., provide more interesting curricula, incorporate technology, provide students with research experiences, increase engagement of college students with industry, encourage STEM faculty to devote more attention to teaching, etc.), and urge government to support more research on improving STEM pedagogy and educational materials.

This formulation—more money and more information—is popular because it avoids the politically difficult problems of challenging existing institutions and interests, including teachers' unions and colleges and universities. To be sure, some targeted and smart increases in investments in STEM education and more knowledge of what works and better efforts to disseminate it are needed, as we discuss throughout this report. But lack of money is not the central problem. Nor is lack of knowledge of "what works." There is a plethora of information, much of it generated in the last decade by research on how to help students effectively learn STEM. In short, neither the "more money" nor the "more information" solutions are the centerpiece of an effective solution. Instead, new kinds of institutions, real incentives for performance, and better information on the performance of educational institutions are key.

The "build it and they will come" approach to improving K–20 has not worked and is not likely to work for a simple reason: the recommendations always say "what," but never "how." The key question is not what to do, but how to get it done. As we will discuss, most educational institutions, either at the K–12 level or the undergraduate and graduate level have little incentive to produce more and better graduates, especially graduates with the kinds of skills needed by industry. It's not a failure of imagination or knowledge; it's a failure of will on the part of institutions. And until policies are put in place to address the "will" factor, change will be halting. Toward that end, creating incentives for educational institutions to change, coupled with providing more information to students, parents and employers on performance, can motivate more institutions do STEM differently and better.

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More Requirements and Mandates Won't Solve the Problem

The fourth limitation of the prevailing "Some STEM for All Approach" is that it ignores the central enabler of effective STEM education: motivated and interested students. The key is designing an educational system, particularly in grades 9 through 12, that respects the desires of students to be active learners. If we want more STEM learners, we need to have students who want to learn STEM.

Yet, core components of the "Some Stem for All" approach are more requirements and tougher standards. If we just require students to take even more STEM courses, and require them to pass STEM standardized tests then, the thinking goes, we will have gone a long way toward solving the problem. Yet, forcing all students to take even more math and science courses, along with an expanding array of other requirements, won't result in more students who want to learn STEM and become STEM workers. In fact, telling students what they have to know and giving them almost no opportunity to follow their own unique interests and passions is a recipe for what we have today: high levels of high school dropouts and disengagement. Indeed, the latest High School Survey of Student Engagement (HSSE) found that two-thirds of American high school students are bored every day in class.

This is not the kind of environment for developing passion about STEM. Needed is an environment where students have much greater ability to follow their interests and passions. Recognizing that not all students are interested in STEM and that those who are will embrace different aspects of the curriculum will be an important start in reshaping STEM education in the nation. This means significantly reducing requirements in high school, and opening up a wider array of educational opportunities for high school students, including specialty STEM high schools, online learning, video game learning, project-based learning, and increased ability to take college STEM courses while in high school.

Educating Students in a Vacuum Won't Solve the Problem

For too long we have assumed that students learn in schools, colleges and universities and then either show up (or not) at employers' doors, with both parties hoping hirees have the right skills to succeed. By focusing so much on what goes on in the schools (better teachers, more standards, etc.) the "Some STEM for All" approach largely perpetuates that assumption. If we are to create the kind of dynamic STEM education system the nation needs whereby the education system, particularly higher education, is better at producing the kinds of workers that are needed by the economy and the kinds of workers who can drive innovation and innovation-based jobs in the United States, we need to create a STEM education system with much closer links to industries that employ STEM workers. Students need to be able to do real research earlier in their educational process. They need to have more access to experience within real organizations where technology is being developed and used. Clearly, industry appears willing to be part of this process, if permitted. A large number of U.S. technology companies from a variety of industry sectors have active programs to help improve STEM education.[3] But if STEM education is to be more effective, partnerships with industry need to be more systemic and deeper.

THE CASE FOR AN "ALL STEM FOR SOME" APPROACH

Rather than base STEM policy on the "Some STEM For All" paradigm, we propose that it be based on an "All STEM for Some" approach. In this approach, the purpose of driving STEM education is not principally to create economic opportunity for individuals; it's to provide the "fuel" needed to power a science- and technology-driven U.S. economy. Without the right number and quality of STEM-educated Americans, the U.S. innovation economy will continue to falter, and with it, economic opportunity—not just for STEM grads, but for tens of millions of other Americans employed in industries enabled by American science and technology. Thus, the "All STEM for Some" framework suggests a different approach—to work to actively recruit those students who are most interested in and capable of doing well in STEM and to provide them with the kind of educational experience they need to make it all the way through the educational pipeline—a B.S. STEM degree or advanced STEM graduate degree—and come out ready, able, and willing to contribute to growing the U.S. innovation economy.

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It is important to articulate what this does and does not mean. This does not mean that an "All STEM for Some" approach is focused on particular socio-economic groups, such as students from high-achieving families going to high-achieving high schools. In fact, the "All Stem for Some" approach would build on the experience of public high schools like the School of Science and Engineering in Dallas, High-Tech High in San Diego, and the Microsoft School of the Future in inner-city Philadelphia. Ensuring that disadvantaged students (as well under-represented groups like girls and women) who are most interested in STEM get a top quality educational experience in STEM clearly would do more to help these students and the U.S. economy then the current "Some Stem for All" approaches.

Many of the approaches we recommend to transform the way STEM is taught at undergraduate and graduate levels would do more to help women and underrepresented minorities obtain STEM degrees than current approaches.

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Many STEM policy advocates argue that STEM is so important to general societal science literacy that America must commit to providing every child the best STEM educational experience money can buy and standards can require. In other words, despite the expense involved in a time of fiscal restraint, STEM is so important that "as a nation we simply can't afford not to make these investments." As this report argues, not only does it look like we can't afford to make these investments (or at least won't have the political will to make them), even if we did, it is unlikely they would effectively address the problem.

Students at the Science and Engineering Magnet in Dallas, Texas work as a group during their chemistry lab class.

The "Some STEM for All" approach assumes that every student wants to, or can, specialize in STEM and have a STEM career. The reality is that career choices are influenced by a wide array of factors (including personality, intelligence(s) and other factors).[4] For example, there is a long tradition of work exploring the link between personality characteristics and choice of occupation, including STEM occupations.[5] And new research suggests that choice of career involves a genetic component. One study found that choice of careers in physical science and engineering (along with fine arts) was about 70 percent more influenced by a person's genetic makeup than career choices such as finance and sales.[6] Ignoring these differences between students and assuming that every student is exposed to a high-quality STEM education will want to and be able to become a scientist or engineer is simply wrong, as would be assuming that every student exposed to high-quality music education and a requirement to take four years of music in high school will want to be or can be a professional musician.

THE OUTLINES OF A NEW APPROACH TO STEM POLICY: THE FIVE I'S

It is time to consider new and fresh approaches to STEM education based on the "Some STEM for All" approach. We offer a number of fundamentally new and creative solutions based on what we call the five I's: new kinds of educational **Institutions**; more **Incentives** to reward institutions for producing more high-quality STEM graduates; more **Information** to students, parents, and employers to give them more choice and to drive better performance by educational institutions; capitalizing on student **Interest**; and spurring more **Industry** involvement.

Institutions: As discussed, the prevailing view in the STEM policy community is that existing institutions can do the job, they just need more: more money, more teachers who are better trained, more information about what works. We disagree. Producing more and better STEM graduates will require new institutions, in particular, a large number of new specialty math and science high schools and new kinds of programs and even colleges at the B.S. level.

Incentives: Again, the conventional view of STEM reform is that educational institutions want to do the right thing, they just lack the information. We believe that while more information about what works and what doesn't is helpful, much of what needs to be done is widely known. What we really lack are incentives for institutions to adopt existing best practices. A wide array of barriers, institutional inertia being a major one, get in the way of real transformative change in educational institutions. STEM policy needs to provide incentives—both carrots and sticks—for institutions to move to STEM best practice.

Information: When consumers have better information about markets they normally make better decisions, and those decisions put pressure on organizations to provide better goods and services more efficiently. Yet, in so many areas of STEM education, information is lacking. Students, parents and employers are often unaware of how well STEM education institutions are performing. STEM policy needs to drive much better information about STEM educational institution performance and ensure that this information is widely available for users.

Interest: There is perhaps no deeper and more widely held view in the STEM education community than that which says: we know what students should learn and the best way for America to enhance STEM education is require every student to learn more STEM, regardless of their interests. But an education system, particularly in high school, that ignores the interests of those doing the learning is one that is destined not to succeed. Force can only go so far. We believe that a more effective route to producing the 5 percent or so of workers who have the skills needed to be STEM workers is to embrace a system where student interests and passion for STEM are what drive curricula. This means dramatically reshaping high school education and the direction of education reform to many fewer requirements and much greater opportunity to explore a wide variety of STEM subjects in depth.

Industry: One reason the education system has not produced the kinds and numbers of STEM graduates needed is that it has attempted to accomplish this task in relative isolation from industry and the world of work. Yet closer links to industry, particularly at the undergraduate and graduate levels, would go a long way toward encouraging more students to major in STEM, to stay in STEM to graduation, and to learn the kinds of skills most needed to power the U.S. innovation economy and to ensure that the United States remains internationally competitive.

These issues are discussed in this report; recommendations that emerge from them are detailed in Chapter 12. Rather than present all the recommendations here, we list what we consider the ten most important and transformative.

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1. **Shift accountability measures for high schools from a content-based to a skills-based paradigm.** Skills-based assessments should replace the National Assessment of Educational Progress (NAEP) and No Child Left Behind (NCLB) subject-matter-based tests for high school students.

2. **Substantially pare the breadth requirements/mandatory course lists required for high school graduation.** In order to provide students the opportunity to pursue depth in their K–12 studies, including STEM, states should reduce, not increase course requirements.

3. **Provide funding to the Department of Education to create 400 new specialty STEM High Schools over the next decade.** Expanding STEM high schools to this number will enable slightly more than 1.5 percent of all high school students or about one-third of future STEM practitioners to specialize in STEM.

4. **Establish a national STEM talent recruiting system.** The United States should move from a weak, potentially expensive, and socially inequitable system of STEM talent self-identification, to a thorough, effective, and more equitable system of directed STEM talent recruiting. Identifying, recruiting, and promoting STEM talent from our nation's high schools should become a systematic national endeavor, similar to NCAA basketball recruiting. A key way to develop this system is to engage the hundreds of federal agency-supported high school outreach program coordinators in this role.

5. **Provide substantially more research opportunities for freshman STEM students.** Because undergraduate research is a highly engaging experience with a track record of greatly diminishing student dropout/switch out from STEM, such experiences should be moved to students' first year of college, as a prophylactic against dropout/switch out endemic to the freshman year. To facilitate this transition for the universities, the President should issue an Executive Order requesting 30 percent or more of federal agency-funded undergraduate research experiences be moved to the freshman year and summer following.

6. **Create new kinds of STEM colleges and programs.** Moving STEM undergraduate and graduate education towards a more interdisciplinary model would not only attract more students to STEM, but also improve the quality of STEM education. For truly transformative change to a more thoughtful, interactive, interdisciplinary model of education, the National Science Foundation (NSF) and National Institute of Health (NIH) should allocate grants for up to $20M/year for institutional transformation.

7. **Require all colleges and universities receiving federal money to report results from the National Survey of Student Engagement.** As a "check off" criterion in the certifications and representations section of any grant proposal that provides student support, universities should have to assert that they have publicly posted their National Survey of Student Engagement results. The release of this information will allow parents, teachers, students, funding agencies, and other stakeholders to ascertain that institution's level of student engagement in instructional practices designed to develop high-quality STEM graduates.

8. **Offer prizes of up to $35 million to colleges and universities that have dramatically increased student STEM degrees and maintained those increases over 5 years.** Congress should appropriate $100M a year to the National Science Foundation, for five years, to be matched one to one by philanthropy, for use as prizes to colleges and universities most effectively expanding the number of STEM graduates.

9. **Significantly increase industry co-funded academic research and graduate student fellowships.** Industry-university partnerships for research and fellowships for STEM graduate student support can play a key role in expanding the number of quality STEM graduates. As Congress expands NSF funding, it should target much larger increases to NSF industry-university research partnership programs (while requiring cash match from industry for these programs), and also support a new industry-university graduate research fellowship program.

10. **Develop an industry-ranked list of the best STEM departments.** Industry should create a national ranking of STEM departments that reflects the quality of students (as future employees) produced by that department. This ranking system should reward departments that train students well for industry employment.

STEM EDUCATION SHOULD BE A NATIONAL PRIORITY

It is probably not possible to write a report about STEM today without mentioning China. With its single-minded focus on innovation and STEM education, China is rightly seen as a threat to the U.S. innovation economy. Numerous reports have warned that China is producing vast numbers of STEM college graduates who will be available to power their technology economy. However, as we discuss below, the reason for this is that the Chinese central government rations college slots. If you are a Chinese student and you want to get into and graduate from college, you have a much better chance of doing so if you major in STEM. In the United States, with our focus on individual liberty and choice, such a regimented approach would be rightly rejected. But while the Chinese approach is not appropriate for the United States (and perhaps not even for China), it does reflect a fundamental insight that is lacking in the United States STEM debate. Chinese officials recognize that STEM is more important than other subjects because the overall societal contribution from a STEM graduate exceeds that of a social sciences or humanities major. Such a view is rejected in elite policy circles in Washington (which are populated largely by individuals with law degrees). On what basis is government to say that electrical engineering degrees are more important than French literature degrees or even law degrees? After all, since the average salary of lawyers is higher than that of scientists, the conventional neoclassical economics view would define lawyers as providing more value to society. To paraphrase neoclassical economist Michael Boskin (who famously said "potato chips, computer chips, what's the difference?"), "Art History, Computer Science, what's the difference?" In fact, three times as many high school students take the AP Art History test than the AP Computer Science AB test.

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From an individual's perspective, art history may be as valuable as computer science. And more importantly, from the educational institution's perspective, teaching a student one or the other makes little difference. In both cases students get their degree and the educational institution gets its money. But if we don't produce enough computer

scientists (or engineers, biologists, etc.), America doesn't innovate and create jobs based on innovation. And innovation has huge benefits—what economists call spillovers. On average, companies don't accrue anywhere near all the benefits from their research and innovation; most of it "spills over" to society as a whole. Likewise, STEM workers don't accrue anywhere near the full benefits from their work: most spill over to society. For example, University of Pennsylvania researcher Laurin Hitt found that information technology workers in companies contribute significantly more to output and productivity than non-IT workers, even when controlling for differences in compensation. Moreover, the difference has grown over time.[7] Thus, if we leave it up to the forces of the educational marketplace alone (individuals and educational institutions making their own choices and decisions unaffected by policy), we will end up exactly where we are today—an economy that produces too few qualified STEM workers.

As a result, it's time for the federal government to adopt and implement a coordinated national STEM education strategy that is grounded in an "All STEM for Some" approach and that brings the "five I's" of institutions, incentives, information, interest and industry to bear to transform our STEM educational system.

Chapters 2 and 3 lay out the case for why we need more and better STEM graduates. Chapter 4 then discusses the prevailing approaches to STEM education policy and why these solutions either are unlikely to be implemented—or if implemented, to solve the problem. The prevailing approaches to improving STEM education—"Some STEM for All" at the K–12 level and "Build It and We Hope you Will Come" at the higher education level—have not worked. And even if these were the right approaches, which we argue they are not, they are unlikely to ever get implemented at national scale given the very large costs involved. As such, it is time for a fresh approach to STEM education.

First, we need to recognize that for an innovation economy, we don't need people who, despite being labeled "STEM," have skills or interests that fail to match industry needs. Such individuals are already part of the reason we have so many STEM jobs filled by non-U.S. citizens. What we need are different types of people entirely: people with stronger fundamental skills, deeper knowledge of at least one discipline, and roots in at least two disciplines. We need people who are not only so well grounded they can generate new ideas, but people who also have the skill set to move their ideas into products, i.e., to be entrepreneurs either inside or outside of corporate walls. These are our innovators, who will drive our innovation economy: people with strong fundamental skills who are "Deep Divers," "Interdisciplinary Connectors" and "Entrepreneurs."

We define "Deep Divers," as those who innovate by pushing the boundaries and frontiers of a given discipline yet further, and "Interdisciplinary Connectors" as those who innovate by fusing the offerings of several disciplines. Both are capable of creating a new idea "from thin air." Making that idea into a saleable product is then the role of the entrepreneur."

In chapter 5, we lay out an approach to improving high school STEM education, built around the notion of establishing a fundamental "core" in skills, rather than knowledge, and using that framework to free the curriculum to the point where students can pursue their passion for STEM in depth and become so-called "Deep Divers."

Subsequent chapters examine the skills high school students need to acquire to become productive citizens in general and STEM workers in particular; how to create more Deep Divers at the high school level; how to create more interdisciplinary experts at the college level, and what it takes to infuse STEM graduates with entrepreneurial skills. Creating more Deep Divers, Interdisciplinary Connectors, and STEM entrepreneurs will not only will produce better STEM workers, it will also induce more students to specialize in STEM.

While it's important to produce better STEM graduates, it's also important to produce more of them to serve in both the public and private sectors, particularly if the United States gets serious about putting in place a robust national innovation policy. In chapter 9, we discuss how to create more STEM graduates at the high school, bachelors, master's, and Ph.D. levels, in part by addressing the valves, or "gates" in the STEM production pipeline.

We need to produce STEM innovators via a national system that is tightly synchronized with industry needs—a workforce system that generates people in the right numbers, with the right skills, at the right times. We are entering a period of dramatic change, and our workforce system needs to be able to keep up. Chapters 10 and 11 focus on ensuring we get the skills match and the timing right.

The United States simply don't have much time left. Technology economies are complex ecosystems that require a robust set of related inputs to work: technically capable suppliers, research laboratories, leading-edge technology customers, and not the least, skilled STEM workers. The United States is losing ground rapidly, as other nations make the kinds of private and public investments needed to grow internationally competitive economies.

Finally, Chapter 12 lays out the policy recommendations for making this all happen.

The United States simply don't have much time left. Technology economies are complex ecosystems that require a robust set of related inputs to work: technically capable suppliers, research laboratories, leading-edge technology customers, and not the least, skilled STEM workers. As we noted in *The Atlantic Century* the United States is losing ground rapidly, as other nations make the kinds of private and public investments needed to grow internationally competitive economies.[8] There is still time for us to turn this around. But there could come a time, perhaps as soon as a decade from now, where no matter how attractive we make STEM education, many fewer Americans will pursue it out of concern that job opportunities will not be here in sufficient numbers. If this happens, then even fewer technology companies will be successful in the United States, leading to even lower student interest in STEM, a downward spiral toward a less prosperous nation.

Students at Carnegie Mellon University in Pittsburgh, Pennsylvania work together on a computer programming exercise.

This process has already played out in the U.K. Having stressed liberal arts education and ignored the competitive position of its industries (made worse by recalcitrant labor unions who refused to embrace change), the U.K. saw its technology industry decline significantly between the 1960s and the 1990s. Indeed, between 1973 and 1992, the total increase in U.K. manufacturing output was just 1.3 percent, compared to 69 percent in Japan, 55 percent in the United States, and 32 percent in Germany.[9] We are not yet at the edge of the kind of precipice the U.K. economy went off, but we are dangerously close. Taking bold action to reinvigorate STEM education is one of the steps needed to reverse this fate.[10] The key question is whether we as a nation will be able to do so with the imagination, creativity and boldness needed. Only time will tell. For the sake of our children let's hope the answer is yes.

BOX 1.1: HALF A CENTURY OF STEM REPORTS AND POLICY RECOMMENDATIONS[11]

Ever since Vannevar's Bush's 1945 iconic report, *The Endless Frontier*, there have been regularly occurring reports stressing the importance of STEM education. These reports and the urgency to respond to the shortage of STEM workers gained momentum in the 1980s as the United States faced new competitive challenges from nations like Japan and Germany. And now with the challenge from China, there is renewed attention to STEM. However, most of the reports follow the same themes of the "Some STEM for All" approach. The following is a sample list of reports and some of the main recommendations offered.

VANNEVAR BUSH
Science, the Endless Frontier, 1945[12]

- Scientific "capital" grows when many people are trained in science at strong centers of basic research.
- Train people in science based on ability, not their capacity to pay.

COMMISSION ON HIGHER EDUCATION
Higher Education for American Democracy, Volume 1, Establishing the Goals, 1947[13]

- Double college attendance by 1960.

- Integrate vocational and liberal education.
- Graduate and professional schools should train well-rounded individuals as well as technicians and research specialists.
- Expand Federal support for higher education through scholarships, fellowships, and general aid.
- Distribute Federal aid to education in a way so poorer states' education systems are closer in quality to those of wealthier states.

PRESIDENT'S COMMITTEE ON EDUCATION BEYOND THE HIGH SCHOOL

Final Report, 1957[14]

- Provide a broader array of post-high school opportunities for students, including the community college.
- Establish definite federal higher education policy.
- Provide broader array of financial sources for higher education.

NATIONAL COMMISSION ON EXCELLENCE IN EDUCATION

A Nation at Risk, 1983[15]

- Reduce the shortage of qualified science and math teachers.
- Curriculum should take advantage of the latest developments in technology.
- High schools should require three years of math, three years of science and one half-year of computer science.

NATIONAL SCIENCE BOARD

The "Neal Report," 1986[16]

- Establish undergraduate STEM Education as a high priority.
- Form partnerships between universities, industry and government to boost STEM education.

SIGMA XI

An Exploration of the Nature and Quality of Undergraduate Education in Science, Mathematics and Engineering, 1989[17]

- Facilitate more exchanges of information on innovative STEM curricula.
- Encourage and support the participation of underrepresented groups in STEM.

PROJECT KALEIDOSCOPE

Volume I, *What Works: Building Natural Science Communities*, 1991[18]

- Encourage partnerships in strengthening undergraduate STEM education.
- Reform introductory courses in STEM education.
- Support hands-on educational/research experiences in STEM courses.

AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

Investing in Human Potential: Science and Engineering at the 'Crossroads, 1991[19]

- Target underrepresented groups for recruitment and mentoring in STEM fields.
- Monitor student progress to determine where attrition takes place.
- Examine financial aid, rigidity of programs, and other areas of campus access for ways to make it easier for undecided students to switch into STEM fields.

NATIONAL RESEARCH COUNCIL

From Analysis to Action: Undergraduate Education in Science, Mathematics, Engineering, and Technology, 1996[20]

- Give all students access to supportive, excellent programs in STEM.
- Provide all students with literacy in these subjects by direct experience with the methods and processes of inquiry.

BILL CLINTON AND AL GORE

Science in the National Interest, 1994[21]

- Ensure that STEM education provides the knowledge for high technology jobs.
- Strengthen partnerships with federal government, educational institutions, industry, and state and local governments.
- Raise the scientific and technical literacy of the population.

NATIONAL SCIENCE FOUNDATION

Shaping the Future of Undergraduate Science, Mathematics, Engineering and Technology Education, 1998[22]

- Incorporate principles of inquiry into STEM courses.
- Encourage collaboration between academic departments and with industry to make sure the material in STEM courses matches expectations of employers.

NATIONAL COMMISSION ON EDUCATING UNDERGRADUATES IN THE RESEARCH UNIVERSITY

Reinventing Undergraduate Education: A Blueprint for America's Research Universities, 1998[23]

- Encourage research experiences and interdisciplinary work early in the undergraduate experience, preferably in the first year.
- Course work and partnerships across departments should make efforts to incorporate information technology.

GOVERNMENT-UNIVERSITY-INDUSTRY RESEARCH ROUNDTABLE
Stresses on Research and Education at Colleges and Universities, 1994[24]

- Provide students with a wider array of research experiences.

NATIONAL RESEARCH COUNCIL
How People Learn, 1999[25]

- Utilize IT to incorporate real-world problems into classrooms.
- Increase opportunities for learners to receive feedback on their work.
- Conduct extensive evaluation research on the use of technologies in classrooms.

THE NATIONAL COMMISSION ON TEACHING
Before It's Too Late, ("The Glenn Commission"), 2000[26]

- Universities need to work with area schools to make sure teacher preparation programs address local needs.
- Evaluate and track teacher progress following graduation.
- Provide incentives for students to become math and science teachers.

NATIONAL SCIENCE & TECHNOLOGY COUNCIL
Ensuring a Strong U.S. Workforce, 2000[27]

- Support research on expanding underrepresented groups in STEM education.
- Encourage partnerships to lower barriers for underrepresented group in STEM.
- Support federal programs based on how they foster a 21st century STEM workforce.

NATIONAL RESEARCH COUNCIL
Adding It Up, 2001[28]

- All five strands of mathematical proficiency (conceptual understanding, procedural fluency, strategic competence, adaptive reasoning, and productive disposition) should guide the teaching of mathematics.
- Efforts to improve students' mathematics learning should be informed by scientific evidence, and their effectiveness should be evaluated systematically.
- Undertake additional research on the nature, development, and assessment of mathematical proficiency.

U.S. COMMISSION ON NATIONAL SECURITY/21ST CENTURY
Roadmap for National Security: Imperative for Change, "Hart/Rudman Commission," 2001[29]

- Increase STEM literacy.
- Pass the National Security Science and Technology Education act to increase the production of scientists, engineers, and science and math teachers.

ACCREDITATION BOARD FOR ENGINEERING & TECHNOLOGY
Accreditation Criteria, 2001

- Engineering education programs must have detailed objectives and an evaluation process by which to confirm those objectives are met.
- Engineering education must be more than knowledge of relevant scientific fields and the ability to conduct research.

BUSINESS-HIGHER EDUCATION FORUM
Building a Nation of Learners: The Need for Changes in Teaching and Learning to Meet Global Challenges, 2003[30]

- Focus education on lifelong learning skills.
- Assess students on academic achievement and skills.

NATIONAL RESEARCH COUNCIL
Bio 2010: *Transforming Undergraduate Education for Future Research Biologists*, 2003[31]

- Promote transfer of knowledge across fields.
- Create an institutional culture supportive of making effective changes.
- Revamp facilities to accommodate interdisciplinary approaches.

AMERICAN ASSOCIATION OF PHYSICS TEACHERS
Strategic Programs for Innovations in Undergraduate Physics (SPIN-UP): Project Report, 2005[32]

- Invest limited funds focusing on system level transformation.
- Encourage research opportunities for students.

NATIONAL RESEARCH COUNCIL
Evaluating and Improving Undergraduate Teaching in Science, Technology, Engineering, and Mathematics, 2003[33]

- Quality teaching and effective learning should be well-understood institutional priorities.
- Judge teaching effectiveness by quality of student learning.
- Faculty should be encouraged to develop interdisciplinary curricula.
- Develop support system that encourages and rewards faculty professional development and innovation in curricula.

NATIONAL RESEARCH COUNCIL

Beyond the Molecular Frontier: Challenges for Chemistry and Chemical Engineering, 2003 [34]

- Chemists and chemical engineers need to be prepared for interdisciplinary work.
- Get students into research experiences as soon as possible.

NATIONAL RESEARCH COUNCIL

Engaging Schools: Fostering High School Students' Motivation to Learn, 2003[35]

- Restructure comprehensive urban high schools to create smaller learning communities.
- Eliminate both formal and informal tracking by ability.
- Schools guidance and counseling should be diffused among staff and teachers, supported by professionals.

MATHEMATICAL ASSOCIATION OF AMERICA

Undergraduate Programs and Courses in the Mathematical Sciences: CUPM Curriculum Guide, 2004[36]

- Work with partner disciplines to make sure that math courses they offer take advance of student progress in mathematical skills.
- General education or introductory math course should improve reasoning, quantitative, and communications abilities of students taking them.

BUILDING ENGINEERING AND SCIENCE TALENT

The Talent Imperative: Meeting America's Challenge in Science & Engineering, ASAP, 2002[37]

- Scale-up successful practices in improving participation from underrepresented groups.

NATIONAL ACADEMY OF SCIENCES

Facilitating Interdisciplinary Research, 2004[38]

- Colleges and funding organizations should support interdisciplinary work.

COMPUTER SCIENCE TEACHERS ASSOCIATION, ASSOCIATION FOR COMPUTING MACHINERY

The New Educational Imperative: Improving High School Computer Science, 2007[39]

- Require new high school computer science teachers to have completed an undergraduate degree in computer science or a comparable degree program.
- Provide regular professional development opportunities for computer science teachers.
- Salaries for computer science teachers should be commensurate with those offered in industry to ensure that high-quality candidates apply for teaching positions.

COUNCIL ON COMPETITIVENESS

National Innovation Initiative Summit and Report: Thriving in a World of Challenge and Change, 2005[40]

- Universities need to promote an innovation-oriented culture.
- Equip the workforce with more than literacy in reading, math and science.

BUSINESS ROUNDTABLE

Tapping America's Potential: The Education for Innovation Initiative, 2005 [41]

- Pass a broader version of the 1958 National Defense Education Act.
- Integrate real world experiences into curricula.
- Encourage private-sector partnerships to facilitate STEM measurement and assessment.

THE NATIONAL ACADEMIES

Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future, 2007[42]

- Increase investment in the talent pool.
- Develop scholarships for potential K–12 STEM teachers.
- Develop undergraduate scholarships for citizens who are STEM majors.
- Increase support for early career researchers.
- Expand specialized STEM high schools.

AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

A System of Solutions: Every School, Every Student, 2005[43]

- Document how well education models are working.
- Student achievement plans must be broadly understood and accepted by stakeholders.
- Collect the right data in the right way to measure educational effectiveness.

NATIONAL ACADEMY OF ENGINEERING

Educating the Engineer of 2020: Adapting Engineering Education to the New Century, 2005[44]

- Encourage research in engineering education.
- Colleges should review the standards for faculty qualifications and expectations to make sure they can provide the right mix of knowledge and experience to their students.
- Encourage interdisciplinary learning in undergraduate engineering education.

COMMISSION ON THE FUTURE OF HIGHER EDUCATION

"A Test of Leadership," 2006[45]

- Increase communications between higher education skills and high schools to improve the preparation of students for college.

- Establish a database on universities to better understand the admissions, cost, and completion data of these schools.

NATIONAL RESEARCH COUNCIL
Taking Science to School, 2007[46]

- Revise standards and curricula to reflect new models of childrens' thinking.
- Structure standards and curricula such that they identify a few core ideas in a discipline and elaborate how those ideas can be developed over grades K–8.
- Leaders in science education should provide teachers with models of classroom instruction where students investigate and then talk and write about their observations.
- School systems should ensure that teachers experience sustained science-specific professional development in preparation and while in service.

U.S. DEPARTMENT OF EDUCATION
Report of the Academic Competitiveness Council, 2007[47]

- The federal government should promote effective practices through improved evaluation and/or implementation of proven research-based instructional materials and methods.
- Federal agencies should improve coordination of their K–12 STEM education programs with states and local school systems.
- Funding for federal STEM education programs should not increase unless a plan for rigorous and independent evaluation is in place.

NATIONAL GOVERNORS ASSOCIATION
Building a STEM Agenda, 2007[48]

- Align state K–12 STEM standards with postsecondary and workforce expectations.
- Develop a communications strategy to engage the public in the urgency of improving STEM education.
- Support the continued development of K–12 data systems to track the STEM preparation of students.
- Create and expand the availability of specialized STEM schools.

ACHIEVE, INC.
Out of Many, One, 2008[49]

- States should work together to develop unified core standards in education.
- States should benefit from analysis of their standards through comparison with American Diploma Project benchmarks.

NATIONAL MATHEMATICS ADVISORY PANEL
Foundations for Success, 2008[50]

- Streamline mathematics curricula and emphasize a well-defined set of critical topics in the early grades.
- Instructional practice should be informed by high-quality research on child learning processes.
- Encourage rigorously evaluated initiatives for attracting and appropriately preparing prospective teachers and for retaining effective teachers.

NATIONAL GOVERNORS ASSOCIATION, COUNCIL OF CHIEF STATE SCHOOL OFFICERS, ACHIEVE
Benchmarking for Success, 2008[51]

- Upgrade state standards by adopting a common core of internationally benchmarked standards in math and language arts.
- Leverage states' collective influence to ensure that textbooks, digital media, curricula and assessments are aligned to internationally benchmarked standards.
- Revise policies for recruiting and developing teachers to reflect the practices of top-performing nations around the world.
- Hold schools and systems accountable through monitoring, interventions and support.

NATIONAL RESEARCH COUNCIL
Learning Science in Informal Environments: People, Places and Pursuits, 2009[52]

- Develop information environments for science learning through community-educator partnerships.
- Develop educational tools through iterative processes involving learners, educators, designers, and experts in science, including human learning and development.
- Integrate questions, everyday language, ideas, concerns, worldviews and histories into science learning experiences.

THE CARNEGIE CORPORATION OF NEW YORK AND INSTITUTE FOR ADVANCED STUDY
The Opportunity Equation: *Transforming Mathematics and Science Education for Citizenship and the Global Economy*, 2009[53]

- Mount campaigns to generate public awareness of math and science.
- Endorse the creation of common, national standards that are fewer, clearer, and higher in mathematics and English language arts.
- Invest in the analysis of supply and demand for science and math teachers, especially in high-need school districts and schools.

- Alter certification requirements to allow qualified candidates to enter teaching by innovative and rigorous alternative routes.
- Invest in sophisticated online professional development systems that facilitate learning communities and cyberlearning by teachers.

NATIONAL ACADEMY OF ENGINEERING
Engineering in K–12 Education, 2010[54]

- Fund long-term research to confirm and refine the findings of earlier studies of the impacts of engineering education on student learning.
- Determine how science inquiry and mathematical reasoning can be connected to engineering design in K–12 curricula and teacher professional development.
- K–12 engineering curricula should be developed with special attention to features which appeal to students from these underrepresented racial and ethnic groups.

OFFICE OF EDUCATIONAL TECHNOLOGY,
U.S. DEPARTMENT OF EDUCATION
Transforming American Education: Learning Powered by Technology, 2010[55]

- Develop and adopt learning resources that use technology to embody design principles for the learning sciences.
- Use technology to provide access to the most effective teaching and learning resources, especially where they are not otherwise available.
- Conduct research and development that explores how gaming technology, simulations, collaboration environments, and virtual worlds can be used in assessments to engage and motivate learners and to assess complex skills.
- Ensure that all students and educators have access to a comprehensive technology infrastructure for learning when and where they need it.

CHAPTER 2:

Why STEM Education?

Student at High Tech High in San Diego, California.

Before examining whether the United States experiences a shortage of STEM workers, it's important to first discuss why STEM workers and, by extension, technological innovation are important. Innovation—the improvement of existing or the creation of entirely new products, processes, services, and business or organizational models—drives long-run economic growth, competitiveness, and quality-of-life improvements.

Countries seek to spur more innovation for three primary reasons. First, innovation helps countries realize an economy characterized by a consistently improving standard of living, which can only be achieved by continuously increasing productivity levels. In fact, the U.S. Department of Commerce has found that technological innovation has been responsible for as much as 75 percent of the growth in the American economy since World War II.[56] Through its contributions to total factor productivity (TFP) and capital deepening, innovation appears directly responsible for at least 55 percent of U.S. productivity growth from 1959 to 2005.[57] Some studies have estimated that innovation drives up to 90 percent of per-capita income growth.[58] Additionally, differences in total factor productivity per worker explain 90 percent of the cross-country variation in the growth rate of income per worker.[59] Innovation achieves its impact by enabling the productivity improvements that lie at the core of economic growth; for example, the innovative use of information technologies has accounted for half of U.S. productivity growth over the past 15 years.[60]

Science-based innovation is particularly important. The societal return on investment from publicly funded research and development (R&D) are estimated to range from 20 percent to 67 percent.[61] Economist Edwin Mansfield estimates that the societal rate of return from investment in academic research is as high as 40 percent (updating earlier work estimating the rate of return at 28 percent).[62] Coe and Helpman find that societal rates of return on R&D are very high, both in terms of domestic output and international spillovers.[63]

Innovation also leads to job growth. As the Organization for Economic Cooperation and Development (OECD) found in a definitive review of studies on productivity and employment, "Technology both eliminates jobs and creates jobs. Generally it destroys lower-wage, lower-productivity jobs, while it creates jobs that are more productive, higher-skilled, and better-paid. Historically, the income generating effects of new technologies have proved more powerful than the labor-displacing effects: technological progress has been accompanied not only by higher output and productivity, but also by higher overall employment."[64] Using cross-country firm-level data, the OECD has shown that technology-using industries have higher than average productivity and employment growth.[65]

Second, countries seek innovation to boost the competitiveness of their traded sectors in international markets, leading to increased exports and better terms of trade. The growth of international trade also makes it increasingly important for the United States to innovate. Low-wage nations can now more easily perform labor-intensive, difficult-to-automate work. Indeed, it has become difficult for the United States to compete in such industries as textiles and commodity metals. Notwithstanding the efforts of countries like China and India to compete in advanced technology industries, for the foreseeable future their competitive advantage should remain in more labor-intensive, less complex portions of the production process. By contrast, the United States' primary source of competitive advantage should be in innovation-based activities that are less cost-sensitive. To illustrate, a software company can easily move routine programming jobs to India where wages are a fraction of U.S. levels. There is less economic incentive for moving advanced programming and computer science jobs there because innovation and quality are more important than cost in influencing the location of these jobs.

Finally, nations look to leverage innovation in order to continually develop new and more effective ways of meeting societal and individual needs.[66] Innovation has been and will likely continue to be central in driving improvements in health care, education, transportation, and environmental protection. Innovation will be indispensible to helping societies address difficult global challenges, such as developing sustainable sources of food and energy, combating climate change, meeting the needs of growing and aging populations, raising billions out of poverty, and achieving shared and sustained global prosperity.

Science- and technology-based innovation is impossible without a workforce educated in science, technology, engineering and math.

For example, innovation has profoundly improved health quality and life expectancy. Innovations in health care practices, techniques, management, and public health have increased life expectancy so rapidly that half the babies born in developed countries in 2007 will live to be at least 103—meaning that, life expectancy, just 49.2 years in 1900, has doubled over the last century. Innovation is driving the emergence of gene therapies, synthetic biology, and personalized medicine that offer the promise of individually tailoring responses to once chronic or incurable ailments and diseases. Innovation will be central to "bending the cost curve" of our health system; for example, the implementation and use of health IT in the United States could save as much as $80 billion annually. Innovation will be indispensible to meeting growing global energy demand while simultaneously sustaining global growth and decreasing the environmental impact of energy consumption. The challenge remains enormous, but there are positive signs. For example, between 1997 and 2007, the U.S. economy became more emissions efficient. Carbon intensity declined even as GDP substantially increased, with information technology playing a crucial role in moving the economy from atoms to digits.

Science- and technology-based innovation is impossible without a workforce educated in science, technology, engineering and math. As a result, it behooves the United States to support strong science, technology, engineering, and mathematics (STEM) education, especially as our competitors recognize the links between STEM education, greater research, and increased innovation. As the OECD observes, "Education systems play a broad role in supporting innovation because knowledge-based societies rely on a highly-qualified and flexible labor-force in all sectors of the economy and society. Innovation requires the capacity to learn continually and upgrade skills."[67] Since innovation and productivity are supported by a highly educated workforce, higher education attainment has become an important component of economic success, particularly in higher wage nations that can compete less effectively in lower skilled, routinized work.[68]

> **Just as we would be unable to expand industry if we lacked the natural resource materials to build the factories (e.g., cement), or energy to power the plants, we cannot expand our technology economy without the needed human resources, in this case high-quality STEM graduates.**

As we discuss in Chapter 3, some may argue that we don't really have a STEM worker shortage. With some companies moving some R&D and technical jobs offshore, we don't really need to be focused on producing STEM jobs, so some claim, or we can always rely on immigrants with STEM degrees, as we do now. But this ignores three key facts. First, as discussed in Chapter 3, the number of STEM jobs is projected to grow over the next decade faster than other jobs. Second, we may not be able to rely on high-skill foreign STEM talent too much longer, as other sending nations, like China and India, successfully grow their tech economies and universities. Finally, if the United States is ever to turn its economy around, including eliminating the massive trade deficit, we will have to do it largely through science and technology-based industries. If we were to eliminate the trade deficit by expanding exports, many of these exports would likely be in technology based sectors. We would need to employ large numbers of additional STEM workers. Just as we would be unable to expand our industry if we lacked the natural resource materials to build the factories (e.g., cement), or energy to power the plants, we cannot expand our technology economy without the needed human resources, in this case high-quality STEM graduates.

CHAPTER 3:

Is there a STEM Worker Shortage in the United States?

Given the numerous press accounts and calls by elected officials, corporate leaders and others, coupled with numerous studies arguing for the importance of improving STEM education in the United States, it may seem odd to ask whether there is a STEM worker shortage. While there is a widespread consensus on the need to improve STEM education, some scholars have argued that there are no signs of a shortage. Those calling for significant improvements in STEM education, as well as those arguing that all is well, cite a wide variety of evidence for their claims. One important question is what, if anything needs fixing. Different versions of the question yield significantly different answers for policymakers. Before addressing these different questions, it's important to first define the STEM workforce.

DEFINING THE STEM WORKFORCE

The STEM workforce can be defined in several different ways.[69] First, it is important to distinguish between "STEM" degrees (biological and agricultural sciences; physical sciences; earth, atmospheric and ocean sciences; engineering; various technology degrees; and mathematics and computer science, and all science and engineering (S&E) degrees which also include the social sciences and psychology.[70] The focus of this report is on STEM degrees, not S&E degrees overall.

It is also important to distinguish between STEM-educated individuals and STEM workers. The former have degrees in STEM fields, but may or may not be working in STEM occupations.[71] The latter are those working in occupations having STEM-related tasks and may or may not have degrees in STEM fields.[72] STEM workers include scientists, engineers, and postsecondary teachers in science and engineering subjects. The term sometimes includes technicians and managers as well. Of the seven million U.S. employed workers with STEM degrees (5.4 percent of the non-farm workforce), 52 percent reported that their job was closely related to their highest degree. These individuals are therefore both STEM-educated and STEM workers.[73] Another 30 percent said their job was somewhat related to their highest degree, while only 18 percent said it was not related.[74] Thus, between 50 percent and 80 percent of STEM workers are also STEM educated (or between 2.7 percent and 4.3 percent of the non-farm workforce).

IS THERE A SHORTAGE?
THE CHRONOLOGICAL ANSWER

Many argue that there is a STEM worker shortage because there are fewer STEM-educated individuals or fewer STEM workers now than at some earlier point in time. Some reports focus on specific STEM fields such as computer science or aerospace engineering.[75] Such arguments—either for or against a shortage—must be considered carefully since one can reach significantly different conclusions simply by picking different end points for comparison.

Trends in STEM Graduates

With regards to STEM training, we can start with data on high school graduates. One data source is growth in trends in Advanced Placement (AP) exams. Between 1997 and 2009, the number of high school students taking AP tests more than doubled, increasing 218 percent (Table 3.1). And while the statistics exam (a STEM subject) grew the fastest of any test (albeit from a low base in 1997), none of the other tests with faster than average growth rates were in STEM fields. Some of the differences are striking. Enrollment in the music theory AP test grew by 362 percent, while enrollment in the Computer Science AB AP test grew by just 12 percent. Even Latin Virgil and French Literature test enrollments grew faster than Computer Science AB. In 2008, more than three times as many students took the Art History AP test as did the Computer Science AB test. Clearly, these trends are disturbing if one hopes to have the best students going into STEM fields.

Table 3.1: Trends in High School Advanced Placement Tests, 1997–2009[76]

AP Exam	Total Percentage Increase	Average Annual Percentage Increase
Statistics	1416%	109%
Psychology	708%	54%
English Language & Composition	404%	31%
Music Theory	362%	28%
Economics: Macro	351%	27%
U.S. Government & Politics	319%	25%
Economics: Micro	261%	20%
All Exams	218%	17%
Calculus BC	214%	16%
Art History	208%	16%
Physics B	190%	15%
Spanish Literature	171%	13%
Chemistry	146%	11%
Spanish Language	143%	11%
U.S. History	140%	11%
Physics C: Mechanics	139%	11%
Latin Literature	134%	10%
Computer Science A	130%	10%
Biology	124%	10%
Comparative Government & Politics	118%	9%
English Literature & Composition	110%	8%
Physics C: Electricity & Magnetism	108%	8%
Calculus AB	105%	8%
European History	101%	8%
French Language	54%	4%
German Language	53%	4%
Latin: Virgil	45%	3%
French Literature	30%	2%
Computer Science AB	12%	1%

Note: "All Exams" includes exams not included individually in the table. Only exams administered every year from 1997 to 2009 are included individually.

At the B.S. level, growth in STEM students was fairly steady (about 2 percent per year) from 1993 to 2003, with the growth rate slowing since 2003. This is about the same growth rate as that of the number of overall bachelor's degrees during this time. Most of the growth throughout the period was in biological, agricultural and environmental sciences and mathematics/computer sciences. (Figure 3.1) In fact, the number of biological sciences degrees grew 65 percent from 1993 to 2007. Much of this growth is due to growth in the biotechnology industry and overall growth in the research budgets of the National Institutes of Health.[77] In contrast, growth in engineering and the physical sciences was minimal. Engineering in fact grew around one percent annually, and actually decreased from 1995 to 2000. The largest year-to-year variations in the number of bachelor's degrees awarded were in mathematics/computer sciences, with double-digit growth between 1998 and 2002 and significant decreases between 2004 and 2007, corresponding with the periods of the dot-com boom and bust (Figure 3.7). In comparison, non-STEM bachelors degrees grew much faster in this decade. From 2000 to 2007, non-STEM bachelor's degrees grew 24 percent, compared to just 16 percent for STEM bachelor's degrees. (Table 3.2)

Table 3.2: Growth of Degrees, 1993–2007[78]

	STEM	**Non-STEM**
Bachelor's degrees	36%	30%
Master's degrees	29%	71%
Doctoral degrees	35%	51%

Figure 3.1: STEM Bachelor's Degrees Awarded, 1993–2007[79]

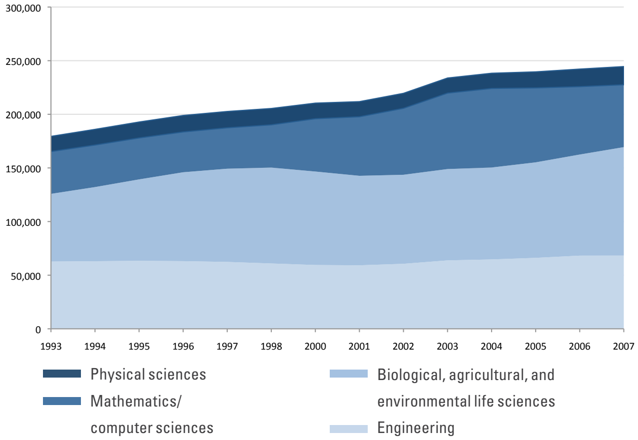
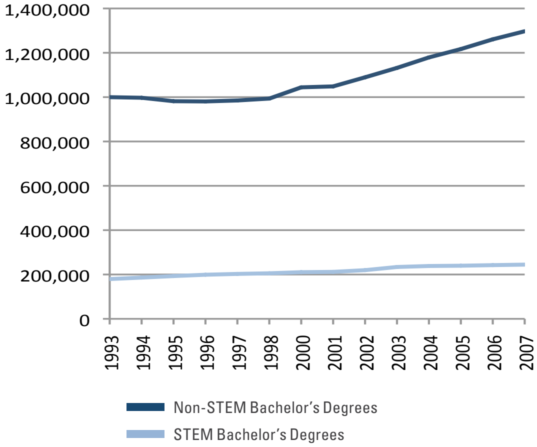


Figure 3.2: STEM vs. non-STEM Bachelor's Degrees, 1993–2007[80]



In contrast to bachelor's degrees, master's degrees grew gradually in the late 1990s and then rebounded after the 2001 recession; after peaking in 2004, they declined by 6 percent in 2007. (Figure 3.3) For the entire period, the number of STEM master's degrees awarded increased by about 2 percent per year from 1993 to 2007, which is about half of the annual growth rate in the number of total master's (4 percent) awarded over this time period. (Figure 3.4)

Figure 3.3: STEM Master's Degrees Awarded, 1993–2007[81]

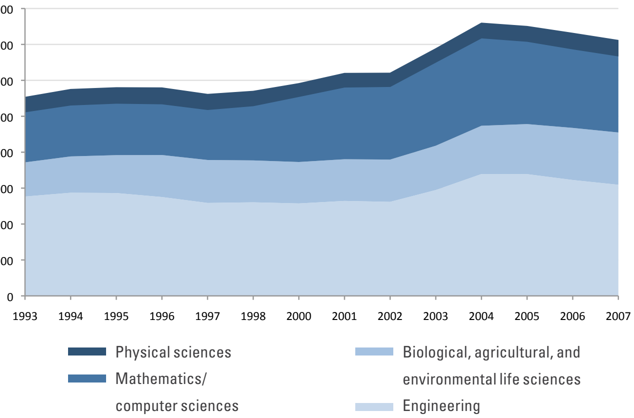
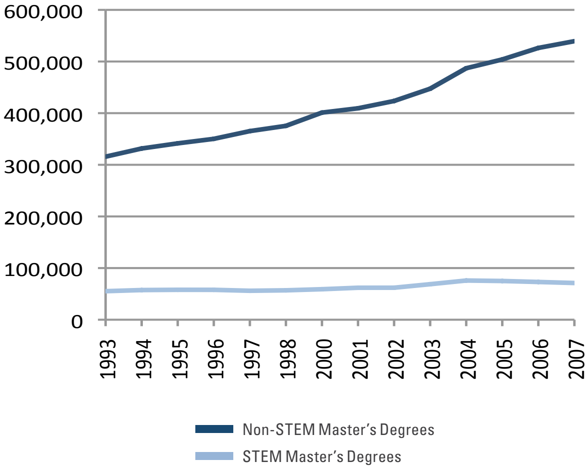


Figure 3.4: STEM vs. non-STEM Master's Degrees, 1993–2007[82]



In contrast, Ph.D. level production increased modestly in the mid-1990s, declined after 1998 and then rebounded after 2002. (Figure 3.5) The number of doctoral degrees awarded increased by about 2.5 percent per year from 1993 to 2007, which is lower than the 3 percent annual growth rate in the number of total doctoral degrees awarded over this time period. (Figure 3.6) However, from 2000 to 2007, STEM doctoral degrees grew slightly faster than non-STEM degrees.

Figure 3.5: STEM Doctoral Degrees Awarded, 1993–2007[83]

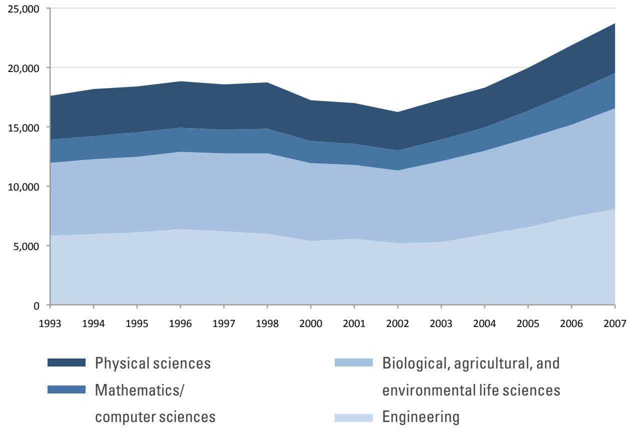


Figure 3.6: STEM vs. non-STEM Doctoral Degrees, 1993–2007[84]

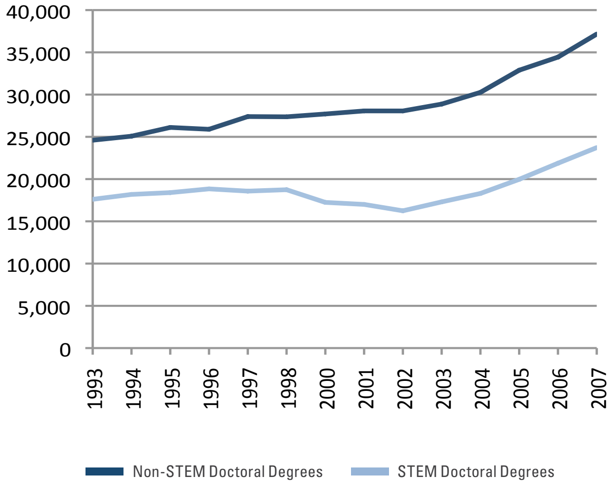
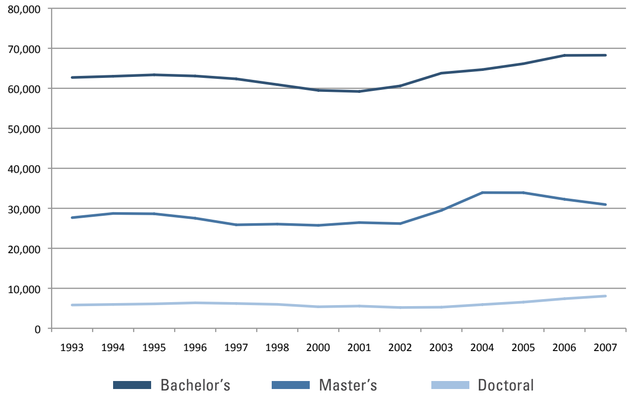
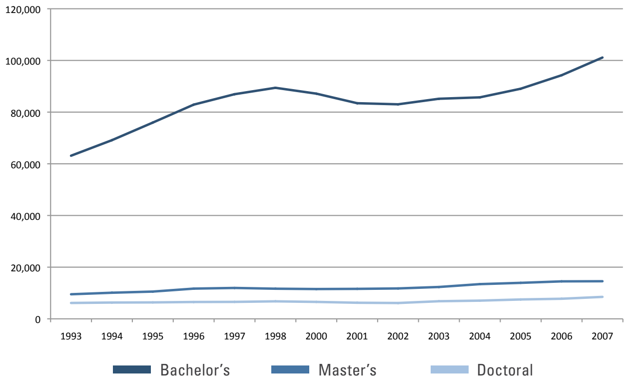


Figure 3.7: STEM Degrees Awarded by Field, 1993–2007[85]

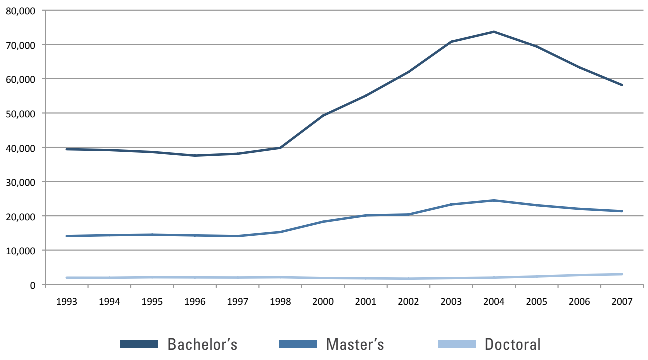
ENGINEERING DEGREE TRENDS



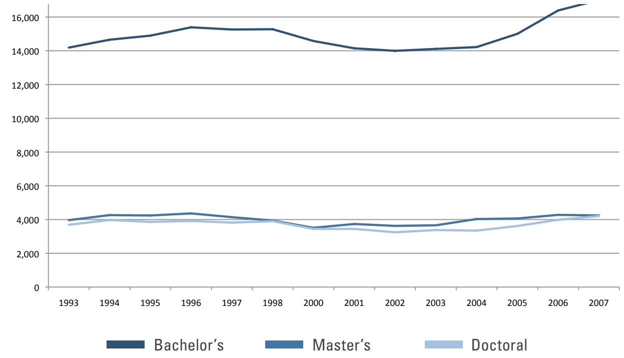
BIOLOGICAL, AGRICULTURAL, AND ENVIRONMENTAL LIFE SCIENCES DEGREE TRENDS



MATHEMATICS/COMPUTER SCIENCES DEGREE TRENDS

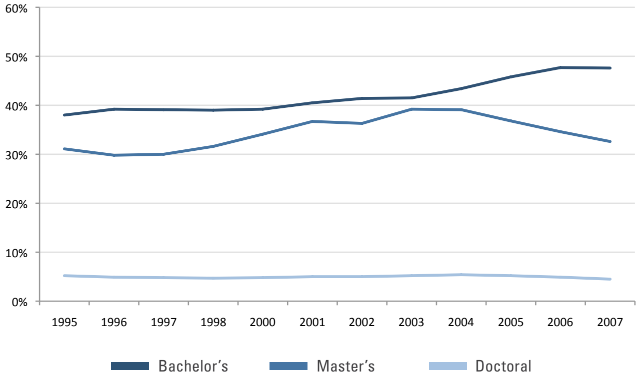


PHYSICAL SCIENCES DEGREE TRENDS



In order to assess the availability of STEM talent for the U.S. economy, its important to look not only at overall graduation rates, but also at the nationality of the graduates. Some foreign graduates end up working in their home countries, particulaly given U.S. immigration restrictions. While the overall number of STEM-trained students is growing, albeit modestly or in some cases slowly, a large fraction of these students, particularly at master's and Ph.D. levels, are not U.S. citizens. (Figure 3.8) While over 95 percent of students graduating with their B.S. in STEM are U.S. citizens, a significant share (74 percent) decide not to go to graduate school in STEM fields and of those who enter the job market, 25 percent go on to jobs that are not STEM-related.[86] There is also recent anecdotal evidence that the share of B.S. degrees awarded to foreign students is increasing, in part as state universities and colleges facing state budget cuts seek foreign students who pay full out-of-state tuition.

Figure 3.8: Share of STEM Degrees Awarded to Foreign Students, 1995–2007[87]

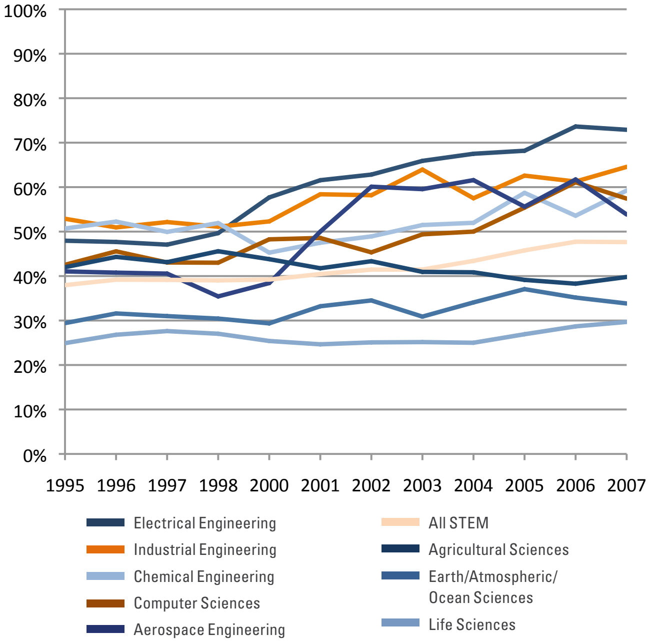


However, the picture is different at the master's and doctoral levels, where a large portion of degrees (about 35 percent and 50 percent respectively) are awarded to temporary U.S. residents. And while the overall level of doctoral STEM degrees awarded to foreign students is approaching 50 percent, in some fields it is significantly higher. For example, almost three quarters of electrical engineering and two-thirds of industrial engineering doctorates are awarded to foreign students. (Figure 3.9)

In some U.S. doctoral university research laboratories it is not unusual virtually all the students to be non-U.S. citizens. In fact, it is the fields most central to U.S. industrial competitiveness (e.g., aerospace engineering, chemical engineering, electrical engineering) that have the highest share of foreign students getting doctorates.

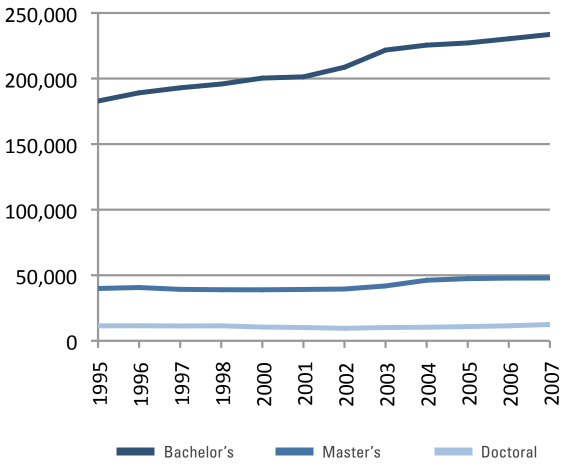
In some U.S. doctoral university research laboratories it is not unusual for virtually all the students to be non-U.S. citizens. In fact, it is the fields most central to U.S. industrial competitiveness (e.g., aerospace engineering, chemical engineering, electrical engineering) that have the highest share of foreign students getting doctorates and the fields that are less central to competitiveness (e.g., earth science, and agricultural science) that have a higher percentage of Americans.

Figure 3.9: Share of Doctoral Degrees Awarded to Foreign Students by Detailed Field of Study, 1995–2007[88]



From 1995 to 2007, the number of bachelor's degrees awarded to U.S. citizens increased at steady rate, by 28 percent. However, the number of master's and Ph.D. degrees awarded to U.S. citizens grew more slowly, by just 20 percent and 9 percent, respectively. (Figure 3.10)

Figure 3.10: STEM Degrees Awarded to U.S. Citizens, 1995–2007[89]



Trends in STEM Workers

STEM workers are defined by the occupations in which they work. Thus, the number of STEM workers equals the number of filled STEM jobs, independent of the degree of the person holding the job. There has been a steady growth in STEM workers/jobs, regardless of how the data are examined. Data from the American Community Survey (ACS) show that the number of S&E-employed workers (which in this survey is actually a narrower definition than STEM, in contrast to the NSF definition of STEM degrees) has increased at a rate of about 2.2 percent per year from 2000–2007, compared to the 1.4 percent annual growth rate for the overall workforce over this period. According to NSF, "the narrow classification of S&E occupations is sometimes expanded to include S&E technicians, computer programmers, S&E managers, and a small number of non-health S&E-related occupations such as actuary and architect. This broader grouping is referred to here as STEM occupations."[90]

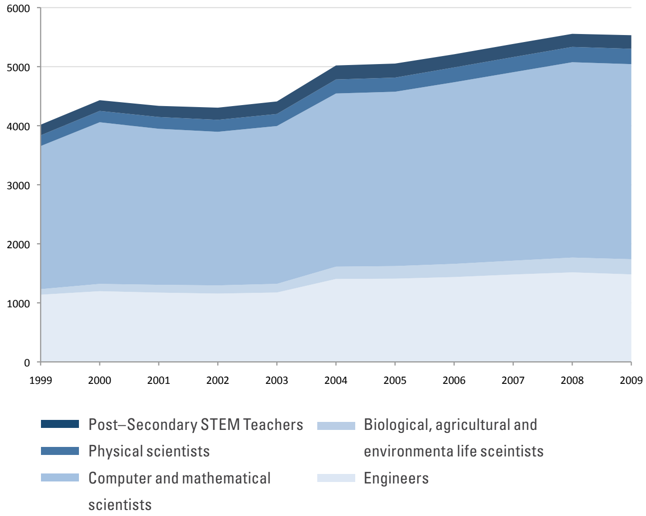
Department of Labor Occupational Employment Survey (OES) data tell a similar story, but also break down results by discipline. (Figure 3.11) They show that computer and mathematical scientists (i.e., the IT occupations), made up the largest fraction of the STEM workforce (60 percent) and engineers the second largest fraction (27 percent) between 1999 and 2009. Biological, agricultural and environmental life occupations had the largest annual growth rate (11 percent) in this decade, but the computer and mathematical occupations, followed by engineering, added the largest numbers of new jobs because of their larger base.

Because the growth in STEM jobs, dominated by B.S.-level occupations, has been so steady over time, it is rare to hear arguments that STEM jobs overall are lacking (leaving aside the current labor market which is depressed overall). This contrasts with claims regarding shortages of students and of qualified workers due to either temporary dips in production or slow growth in particular disciplines.

If we compare the students to jobs, we find the STEM workforce has grown more rapidly on an annual basis between 1990 and 2007 (3 percent to 4 percent) than the number of STEM degree recipients (2 percent). On the face of it this suggests that the STEM education pipeline is not adequate to supply the number of workers needed by the economy. In fact, it is possible that if more STEM graduates were available that the expansion of the STEM workforce would have been even larger; technology companies that possibly expanded offshore due to shortages of STEM talent might have expanded instead in the United States.

However, the gap between growth in STEM jobs and STEM degrees has been largely filled by foreign workers.[91] By 2002, the most recently compiled data on foreign representation in the STEM workforce showed that nearly 20 percent of workers in STEM occupations were foreign-born.[92] The issue of foreign/domestic STEM workers is discussed below.

Figure 3.11: Number of U.S. STEM Workers by Occupation, 1999–2009 (in thousands)[93]



IS THERE A SHORTAGE? THE FUTURE PREDICTIONS ANSWER

Another way to assess whether there is a shortage of STEM workers is to examine predictions about future supply and demand. Every two years, the Bureau of Labor Statistics (BLS) projects the size of the labor force over the next decade. The most recent available projections as of 2010 are those projecting the size of the labor force from 2008 through 2018. (Table 3.3) The estimate does not predict or take into account the severe recession and likely slow growth in the labor market in response. Absent these factors, the STEM labor force was expected to grow 19 percent, almost double that of all occupations (10 percent) and slightly more than comparable occupations in the group of professional and related occupations (17 percent).[94] As in the last decade, the number of new jobs expected to be created between 2008 and 2018 was to be largest for computer and mathematical scientists because of their larger base, but the largest percentage increase (27 percent) was anticipated for biological, agricultural, and environmental life scientists because of growth in the biotechnology and environmental industries.[95]

Table 3.3: STEM Workforce Projections, 2008–2018 (in thousands)[96]

Occupation	2008 Employment	2018 Projected Employment	Change in Employment	Percent Change
All Occupations	150,932	166,206	15,274	+10%
Professional and related occupations	31,053	36,280	5,227	+17%
All STEM Occupations	5,667	6,747	1,080	+19%
Biological, agricultural, and environmental life scientists	279	354	75	+27%
Computer and mathematical scientists	3,540	4,326	786	+22%
Physical scientists	276	317	42	+15%
Engineers	1,572	1,750	178	+11%

Many who warn of shortages in the STEM workforce have cited workforce projections like these, estimating that the expected demand for workers will soon outstrip the supply in the STEM pipeline.[97] Even though the BLS projections are based on a rigorous modeling approach utilizing demographic projections, macroeconomic models, and input-output models, they do not take into account factors such as changes in immigration law, reversals in government acquisition programs, sudden shifts in the global economy, and other exogenous factors that can significantly change occupational demand.[98] Projections point to broad trends, but as date-specific predictions, they are often highly inaccurate, in either direction.

This was evidently the case with the BLS projections for aerospace engineering, which were unable to anticipate or take account of the consolidation of the industry that took place in the 1990s and the downsizing of the defense industry.[98] As stated in a 2009 report that looked at IT workforce projections, "Overall, BLS projections have been good at predicting the actual size of the IT labor force. However, projections often vary with business cycles, being more optimistic during times of growth and more pessimistic during times of workforce contraction."[100] Problems with labor market projections were discussed in detail and improvements recommended by the National Academies in 2000.[101] The National Academies report on *Forecasting Demand and Supply of Doctoral Scientists and Engineers* concludes that the forecasting of job markets is so imprecise that the National Science Foundation should avoid endorsing or producing any single model, for fear of misleading policy makers with highly uncertain predictions:

> If asked to produce forecasts of scientific and engineering personnel for its own use or the use of other agencies, the NSF policy unit should avoid endorsing or emphasizing "gap" models that do not incorporate behavioral adjustment to demand and supply and consequently may give unwary users a misleading impression of likely market outcomes. NSF should avoid suggesting that there is a single best level of detail and model complexity for the forecasts needed by various users and should instead maintain that model structure will depend on user needs and objectives.[102]

The uncertain state of job market forecasts is also noted in the most recent NSF *Science and Engineering Indicators*:

> Projections of employment growth are notoriously difficult to make, and the present economic environment makes them even more uncertain. Conceivably, the worldwide economic crisis will produce long-term changes in employment patterns and trends. The reader is cautioned that the assumptions underlying projections such as these, which rely on past empirical relationships, may no longer be valid.[103]

These problems have been cited by some who claim that there are no shortages in the STEM labor market: the argument goes, there were overly optimistic projections about STEM worker demand in the past, so the projections today are also likely to be overly optimistic. For example, Richard Freeman states:

> In 1990, Richard C. Atkinson, then president of the American Association for the Advancement of Science (AAAS), predicted that, by the year 2000, demand for scientists in the United States would outstrip supply by almost four hundred thousand. He recommended programs to encourage more young people to pursue doctorates in science and engineering. But four years later, there was no evidence of a shortage. Newsweek ran an article on the science workforce under the headline, "No Ph.D.s need apply: The government said we wouldn't have enough scientists. Wrong."[104]

While Freeman is widely cited by STEM shortage skeptics, there were reasons why the BLS projections of that time were not accurate. The projections overlooked two unforeseeable factors, one on the demand side and one on the supply side. First, there were significant unexpected cuts in the federal R&D budget relative to GDP during the early 1990s and slower growth after that, in part due to the end of the cold war.[104] This represented an unanticipated reduction in demand for STEM workers. There was also an increasing reliance on foreign workers, which boosted supply, even despite a lack of domestic STEM-trained workers.[106] These trends, unpredictable at the time of the projections, resulted in no apparent signs of shortages. This shows the difficultly in making labor market projections given the significant impact of exogenous factors.

Overall, projections of future labor shortages or excesses rarely materialize on cue because the models are long term and idealized. Thus, while Table 3.3 suggests a generalized growth in STEM jobs over the next decade, it may be a decade and a half before the jobs materialize, and they may develop on a different scale or with a different mix than that predicted by the table. For this reason, we divide our workforce "quantity" strategy into two additive components: one that can increase numbers gradually, over the long term, across broad segments of STEM (Chapter 9), and one that responds quickly to rapid shifts in job market conditions (Chapter 10). The first is designed to adapt to long-term growth, typical of what BLS predictions speak to; the latter, to short-term reality.

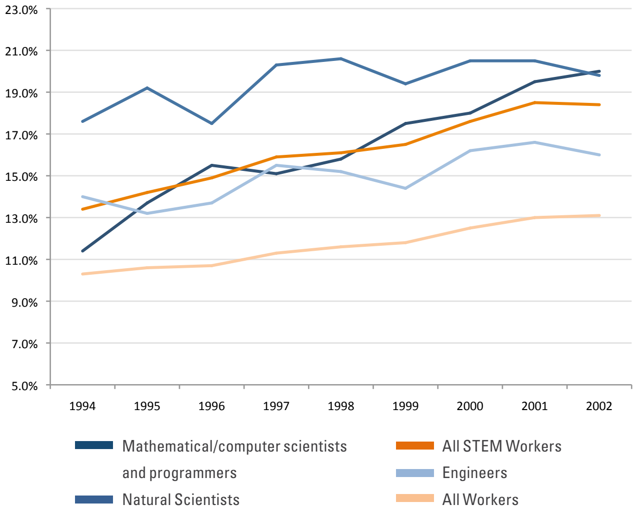
IS THERE A SHORTAGE? THE FOREIGN VS. DOMESTIC WORKER ANSWER

A number reports have argued that there is STEM workforce shortage because the STEM workforce is not fully supplied by internal sources (i.e., U.S.-born STEM workers).[107] Foreign workers comprise a significant portion (18 percent) of the STEM workforce, compared to just 11 percent of the overall U.S. workforce. (Figure 3.12) Of these, about one quarter (or 4 to 5 percent of all STEM workers) are H-1B visa holders; the majority are permanent residents.[108] Many of the permanent residents first come to the United States to study, and then stay to deploy their skills. Seventy percent of foreign Ph.D. students who come to study at U.S. universities are in the United States and paying income taxes two years after completing their degrees.[109]

From the standpoint of the national economy, there appears to be no immediate downside to this supply of foreign labor, although as discussed below there are long-term risks if foreign STEM students and/or workers are less willing to come in the future. The long-term salary trends of engineers and scientists have not been worse than those of the average U.S. worker and the overall salaries much higher (both are evident in Figure 3.23).

However, some argue that wages for domestic STEM workers might have grown even faster without the influx of foreign workers. But as an argument against high-skilled immigration this is flawed on two counts. First, in competitive markets, higher wages are passed on in the form of higher relative prices. And since overall STEM worker wages are 59 percent higher than the average U.S. wage, even higher wages for STEM workers would essentially be passed on in the form of higher prices for the significant majority of Americans who make less. And if wages were to go up even faster for STEM workers, companies in the United States that compete in global markets would lose market share, resulting in relatively fewer STEM jobs. Second, there is evidence that increased high-skill immigration did not result in slower growth in STEM wages. Mithas and Lucas found that H-1B visa holders in IT occupations are actually paid a (small) premium over U.S.-native workers, countering arguments that such individuals are low-wage substitutes for U.S. workers.[1109] Moreover, foreign workers contribute to technological innovation. Foreign workers in the United States. have been patenting at an increasing rate. Considering that the number of patents granted to U.S. residents has remained constant since 2005, U.S. innovation would be declining without the influx of foreign workers.[111]

Figure 3.12: Percentage Foreign Born Workers , 1994–2002[112]



Finally, at least seven studies have examined the role of immigrants in launching new companies and all conclude that immigrants are key actors in this process, creating 15-26 percent of new companies in the technology sector.[113] Because new companies with 20 or more employees account for nearly all new net job creation, one can argue that the influx of foreign-born STEM workers is helping to boost jobs for U.S.-born STEM workers.[114]

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Some discussions with respect to workforce "shortages" and foreign vs. domestic composition of the workforce invoke national security concerns. Certain fields, such as aerospace engineering, involve significant amounts of defense work and U.S. citizenship is a requirement for these jobs. Thus, to see high percentages of foreign-born degree recipients in these fields brings into question whether we have, or will have, enough U.S. citizens to fill needed jobs. But whether the U.S. citizen cadre graduating with such degrees is enough to fill security-sensitive jobs is not clear. The biggest need for U.S. citizens in these industries is at the bachelor's level, and 95 percent of B.A. degree recipients are native-born. Moreover, calls for more U.S. citizen degree production to address security-related job openings have typically stressed future openings, not present ones, such as those in the aerospace industry, suggesting that the present situation is tenable.[115] And, as discussed above, future projections often prove inaccurate.

But questioning whether the foreign-born should remain a significant component of the U.S. STEM workforce really boils down to asking whether the United States should become over reliant on such a key asset. One reason why the United States has been able to attract such a large number of foreign STEM students, particularly at the graduate level, who then stay and contribute to the economy, is its world-class research universities. But that leadership appears to be diminishing, both as a result of cuts in state and federal support for higher education and increased efforts by other nations to establish their own world-class higher education research institutions. In the *Times Higher Education-QS World University Rankings*, the United States had 37 institutions in the top 100 and 58 in the top 200 in 2008. But in just two years by 2010, those numbers fell to 31 and 53 respectively.[116]

In addition, students come to the United States from other nations in part because others from their nation have come before. And they stay for the same reasons. But as other nations' economies develop, the attractiveness of the United States as a destination for foreign STEM students and workers declines. Saxenian documents this, showing that as Taiwan's economy (and universities) developed, Taiwanese STEM students getting degrees in the United States were much more likely to return home to Taiwan.[117]

Today as nations like Indian and China develop, it is certainly possible that fewer of their top students will come to the United States for STEM degrees, and likewise that fewer who do will stay. The Chinese government is certainly aware of this, and it is one reason why it is making a major push to develop a considerable number of new research universities. The Chinese have constructed campuses and science parks to accommodate what it hopes will be a boom in homegrown technological advances. This is part of China's ambitious "Thousand Talents" program, which seeks to lure Chinese-born scientists and engineers in the United States. and other countries back to China.[118]

Moreover, until recently, the United States enjoyed somewhat of a "buyer's market" as many other nations were either relatively closed in terms of accepting top STEM talent from around the world, or didn't need it as they had a small technology industry. Both situations are changing. As David Hart has documented, many nations are loosening their restrictions and becoming more open to attracting foreign STEM talent.[119] Moreover, as ITIF has documented, many nations are expanding corporate and government R&D at a much faster rate than the United States, expanding their demand for STEM workers in the process.[120]

Thus, while there is no urgent cause for alarm with respect to a workforce composition that contains a significant fraction of foreign workers specifically, the relatively low share of Americans going into STEM fields does pose a risk to the U.S. economy going forward.

IS THERE A SHORTAGE? THE INTERNATIONAL COMPARISONS ANSWER

Many claiming a shortage of STEM workers in the United States compare the number or quality of U.S. schoolchildren, degree holders and workers to other nations. In addition, some compare U.S. R&D budgets, patents, or publications to those in other countries to argue that overall innovation in the United States is suffering, in part, they say, because of a shortage of STEM workers.

School Test Scores

K–12 math and science test scores are often thought of as an indicator for the available pool of STEM talent.[121] The relatively low test performance of U.S. students relative to students in other countries on the TIMSS (Trends in International Mathematics and Science Study) and PISA (Programme for International Student Assessment) tests have been a particular concern.[122] On the 2007 TIMSS math tests, U.S. fourth-grade students ranked eleventh among students in 36 countries and U.S. eighth grade-students ranked ninth among students in 48 countries. (Table 3.4) However, on TIMMS the United States has shown some progress. Between 1999 and 2007, of 20 nations for which there are comparable data, the United States ranked 4th in improvement in eighth-grade math scores and 6th out of 25 nations in improvement in eighth grade science scores. The United States also made greater improvement in eighth-grade science scores than several international leaders such as Japan, Sweden, Norway and Singapore between 1999 and 2007.

Table 3.4: TIMSS Mathematics Test Scores,
Top 11 nations, 2007 Average=500[123]

GRADE FOUR		GRADE EIGHT	
Country	**Score**	**Country**	**Score**
Hong Kong	607	Chinese Taipei	598
Singapore	599	Republic of Korea	597
Chinese Taipei	576	Singapore	593
Japan	568	Hong Kong	572
Kazakhstan	549	Japan	570
Russian Federation	544	Hungary	517
England	541	England	513
Latvia	537	Russian Federation	512
Netherlands	535	**United States**	508
Lithuania	530	Lithuania	506
United States	529	Czech Republic	504

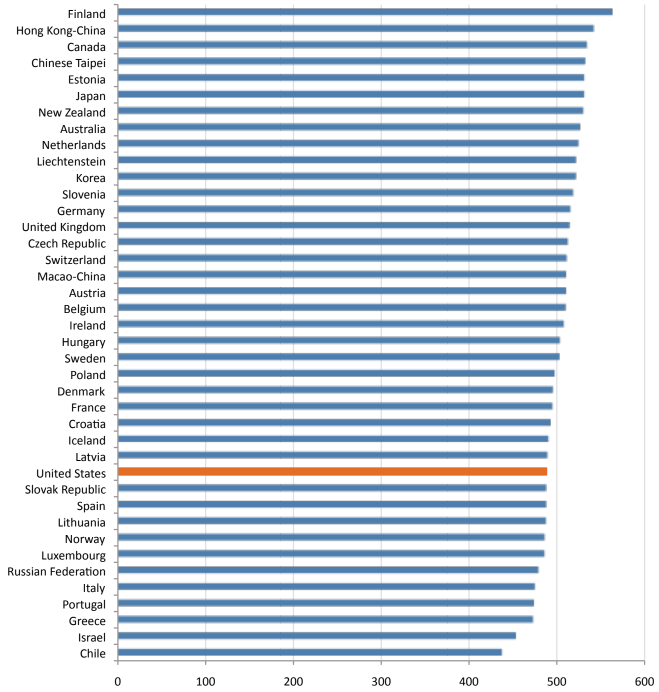
On the PISA test, the United States scores more poorly. In the 2006 assessment, U.S. 15-year-olds ranked below those in 29 other countries in math and 34 other countries in science as shown in Figure 3.13. The PISA test is more a measure of the application of learning to real world situations, suggesting that our low rank here is even more of a problem.[124]

Overall, the United States is not highly ranked internationally in average K–12 math and science test scores. Its test score deficiencies are often cited to suggest that weak STEM education will lead to a shortage of STEM workers in the future. The first *Gathering Storm* report argues:

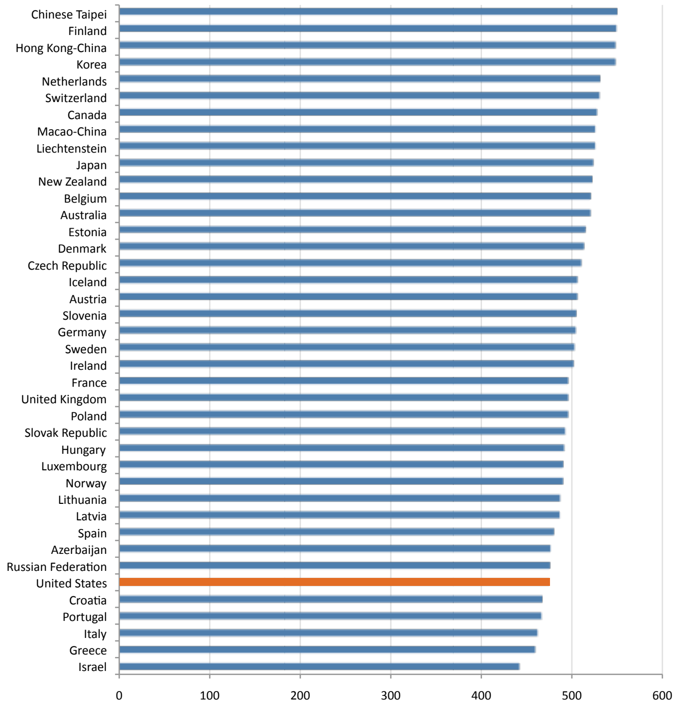
> In general, many Americans do not know enough about science, technology, and mathematics to contribute to or benefit from the knowledge-based society that is taking shape around us. At the same time, other countries have learned from our example that preeminence in science and engineering pays immense economic and social dividends, and they are boosting their investments in these critical fields."[125]

Figure 3.13: PISA Mean Science/Math Scores by Country, 2006[126]

PISA MEAN SCIENCE SCORES



PISA MEAN MATH SCORES



However, Lowell and Salzman argue that "rather than concluding that the United States is behind in the world, it would be more accurate to conclude that the test results show the United States is not the highest performing nation in any single science or math test, but it is one of a very few nations that consistently rank above the international average in tests of academic performance … and the United States is one of the few that show consistent improvement over time across grades and subjects."[127]

While middling performance on academic tests is never a good sign, a key question, rarely raised, is whether the middling performance of our K–12 students on TIMSS and PISA tests translates into middling capabilities of our STEM workforce, on the job. As discussed below, STEM workers represent only a small share of the total workforce. Hopefully it is the portion that performs in the top on these international assessments, but we don't know. As such, we don't really know how well STEM workers are qualified relative to their international peers. No direct assessments of our STEM workforce, or of those likely to become STEM workers, exist. Having a test whose results could be more directly tied to national job skills goals would help us move beyond this broad assessment of all students to a more accurate assessment of differences in capabilities of STEM workers in different nations. One such series of tests is discussed in Chapter 11.

Numbers of Students or Workers

International comparisons are also often made of the size or intensity of the population engaged in STEM jobs or STEM training.[128] The number of first science and engineering degrees awarded by country (in the United States this would be a bachelor's degree) is one such indicator. As shown in Figure 3.14, China has awarded more STEM degrees than the United States in every year from 1998 through 2006. In 2006, China awarded nearly four times as many first S&E degrees as the United States, with most of those degrees in engineering. In 2006, India also likely awarded nearly as many, if not more, STEM degrees than the United States, though recent data is unavailable. At the doctoral level (Figure 3.15), the United States ranks first in STEM degree production, but China's aggressive growth rate is on track to eclipse U.S. production in 2010. For example, a 2005 Business Roundtable report found that, "by 2010, if current trends continue, more than 90 percent of all scientists and engineers in the world will be living in Asia."[129] Such predictions are echoed by many others. The United States does better in terms of number of full-time equivalent (FTE) researchers, having more than any other county, including the EU-27 combined. But the number of FTE researchers in China has been rising rapidly.[130] (Figure 3.16) Between 1999 and 2006, the number of FTE researchers in China grew by 111 percent, faster than any other country.[131] Assuming the historical growth rates of FTE researchers continued for the United States and China, China will have surpassed the United States by 2010.

But such concerns focused on overall numbers are highly misleading. By this definition, technological leaders such as Israel or Sweden should in fact be technological laggards because they graduate so few STEM students compared to larger nations. Obviously if we are looking at the impact of STEM on the overall standard of living in a nation, any accurate comparisons need to be on a per-capita basis. On this basis the picture is different. As shown in Figures 3.17 and 3.18, when controlling for each country's university-age population, the actual rate at which the U.S. residents earn science and engineering degrees is more modest.

Figure 3.14: First Natural Sciences and Engineering Degrees Awarded by Country, 1998–2006[132]

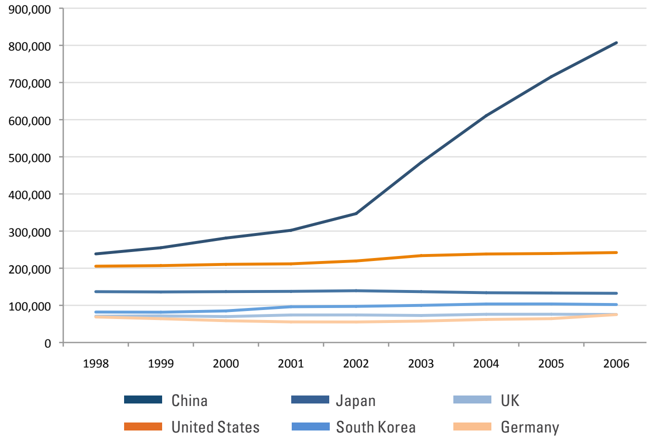


Figure 3.15: Natural Sciences and Engineering Doctoral Degrees Awarded by Country, 1993–2006[133]

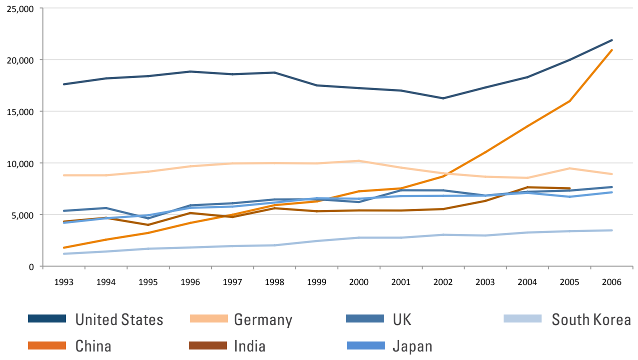


Figure 3.16: Number of Full-Time Equivalent Researchers, International Comparison, 1995–2007 (in thousands)[134]

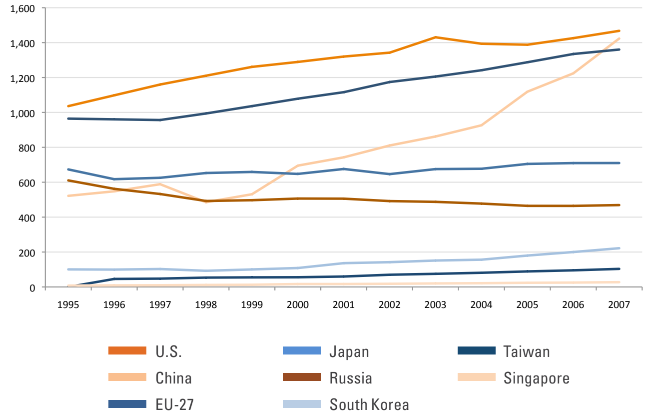
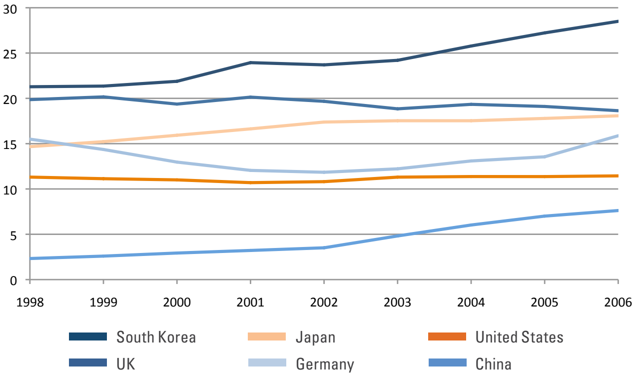


Figure 3.17: First University Natural Sciences and Engineering Degrees per thousand 20–24 year olds, by Country, 1998–2006[135]



In terms of the share of the workforce in science and technology occupations (defined here much more broadly than STEM occupations), the U.S ranked 11th among the 30 OECD countries in 2008. (Figure 3.19) Sixteen percent of the U.S. workforce was in science and technology occupations in 2008, slightly higher than the OECD average of 15 percent.[136]

Figure 3.18: Natural Sciences and Engineering Doctoral Degrees per thousand 20–24 year olds, by Country, 1993–2006[137]

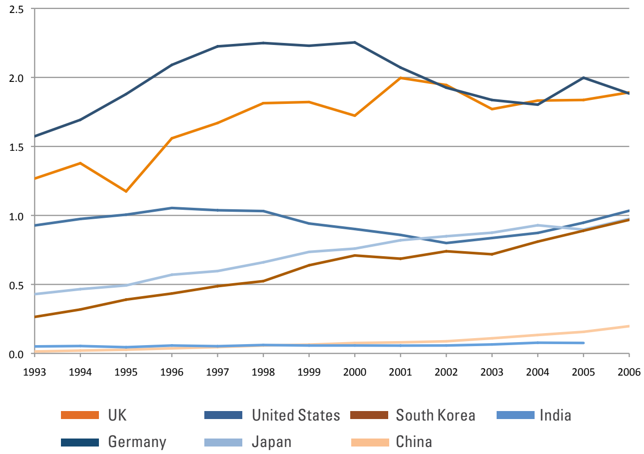
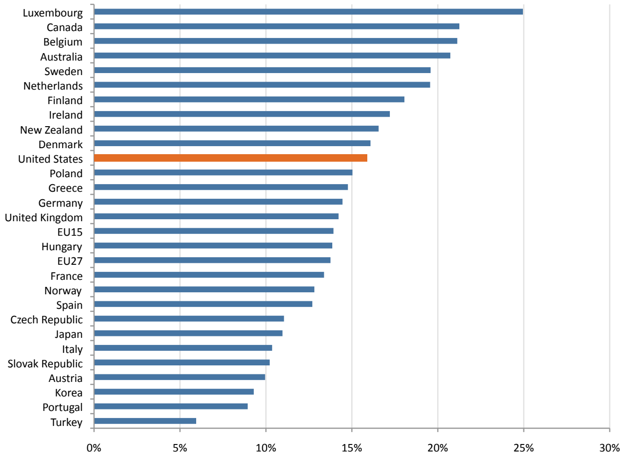


Figure 3.19: Share of the Workforce in Science and Technology Occupations (2008)[138]

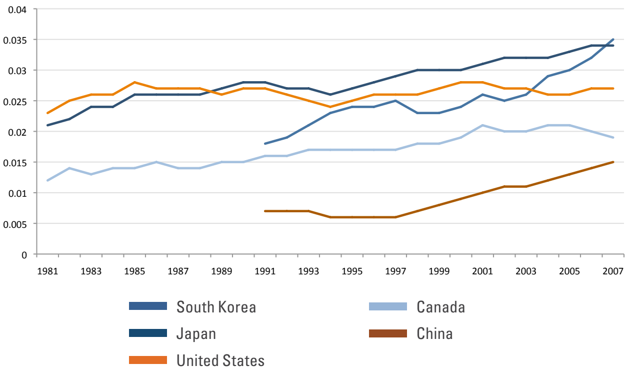


R&D Expenditures

National expenditure on research and development (R&D) strongly influences the demand for STEM degree holders and workers. While declining R&D expenditures would reduce STEM shortages since there would be less STEM work to do, it is also true that a shortage in STEM workers could lead to lower R&D expenditures. Companies in nations with a strong supply of STEM workers tend to expand R&D.

Japan and South Korea are 55 percent and 44 percent ahead of the United States, respectively, in corporate R&D as a share of GDP.[139] (Figure 3.20) Between 1999 and 2006, corporate R&D as a share of total R&D actually declined in the United States, compared to countries like China and Mexico where it increased by 160 percent and 129 percent respectively.

Figure 3.20: R&D Investments as a Share of GDP, 1981–2007[140]



Publications and Patents

The United States is also losing ground in patent and publication production. While U.S. science and engineering publications have leveled off, they are increasing in many other nations. (Figure 3.21) Between 1995 and 2007, publications increased 17 percent in China, for example, compared to just under 1 percent in the United States. While U.S. patent production has grown at about 3 percent per year between 1990 and 2008, the number of patents produced by Asian countries has grown by 16 percent per year over the same time period. (Figure 3.22)

Figure 3.21: International Comparison of Science and Engineering Publication Production (in thousands)[141]

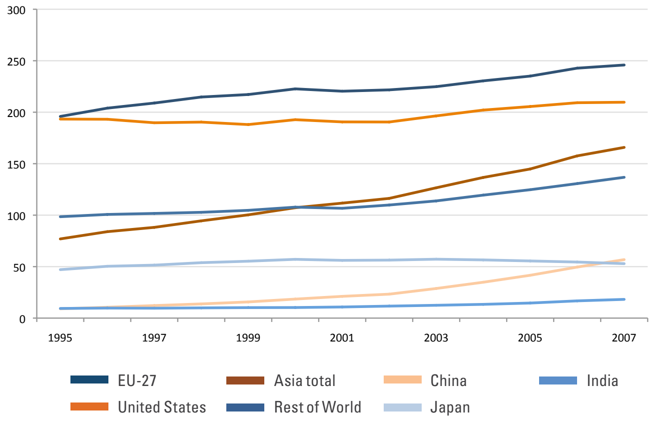
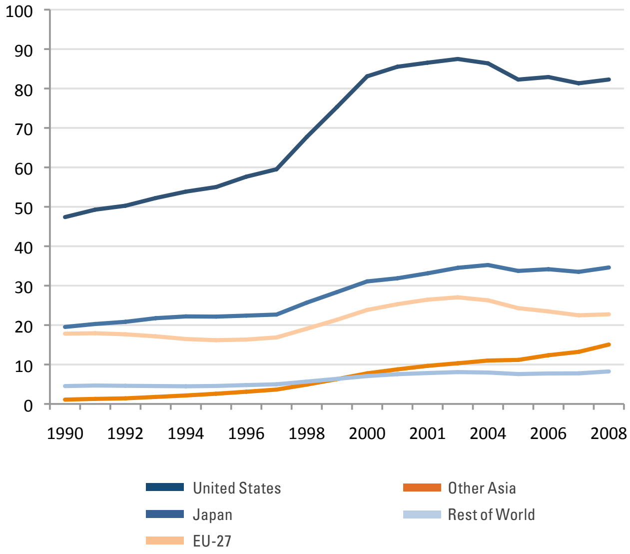


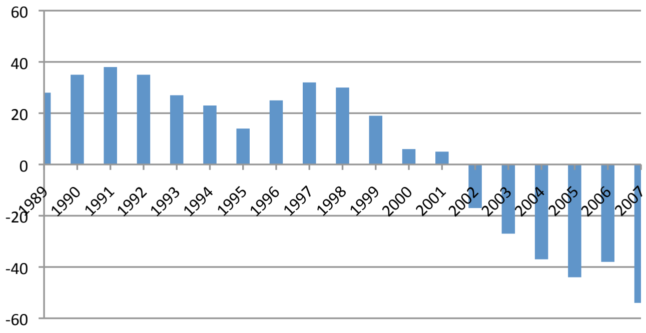
Figure 3.22: International Comparison of Patents Granted (in thousands)



High Tech Trade Balance

Another indicator of eroding U.S. technological competitiveness is the increasing trade deficit in technology areas. The United States has experienced a trade deficit in high-technology products since 2002. (Figure 3.23) Moreover, as a percentage of the overall U.S. trade deficit, the deficit in high-tech products has increased from 4 percent in 2002 to 7 percent in 2007.[142]

Figure 3.23: Total U.S Trade Balance in High-Tech Products in Billions of Dollars, 1989–2007[143]



Looking at indicators such as these, ITIF's *Atlantic Century* report finds that the United States ranks 6th overall of 40 countries and regions in innovation-based competitiveness, and is not the world leader it is often thought to be. Even more striking is that the United States ranked last of 40 countries in improvement in innovation and competitiveness.[144] These findings suggest that that the United States is doing very little relative to other nations to successfully compete in innovation-based economic development.

Overall, whether looking at K–12 test scores, numbers of degrees, STEM workforce intensity, national R&D expenditures, publications, or patents, the U.S. position can be characterized as one of either “eroding” or “already eroded” leadership. While STEM jobs in the United States have increased other countries are more aggressively cultivating an expanded STEM workforce and STEM enterprise. Thus, if we wish to outpace other nations in innovation-based economic activities and the high paying jobs that these provide and enable, the important task is to increase global demand for U.S. STEM workers and their products. There are two ways to do this, both of which need to be pursued. First, the federal government needs a top-down strategy wherein the United States commits to regaining global innovation leadership with a comprehensive suite of trade, tax, research and other strategies. Second, we also need a bottom-up strategy in which we consciously create a generation of STEM workers that has a much larger fraction of innovators, who can create jobs and products at an even faster pace. The latter—alongside a STEM workforce system that produces individual workers in the right numbers, with the right skills, at the right times, to keep a high-pitched innovation economy humming—are the foci of this report.

IS THERE A SHORTAGE? THE ECONOMICS ANSWER

As the prior sections show, most indicators suggest that the United States is not producing enough STEM graduates (especially U.S. citizens and permanent residents) and is losing global share in technology indicators (e.g., patents, R&D, scientific publications) and jobs, in part due to lack of adequate STEM talent. While many individuals and organizations involved in STEM policy rely on such metrics to conclude that there is a problem that needs solving, some conventional neoclassical economists say otherwise. In neoclassical economics, the prima facie evidence of any kind of shortage, labor or otherwise, is clear: increasing prices and expanding supply. Absent price and responding supply increases, there simply cannot be a shortage in these models. Using this conventional approach it is clear that there have been spot shortages in specific fields. But, by these same measures, there have also been few, if any, periods where a clear-cut worker shortage was evident across most or all STEM fields. Each of these points will be examined in more detail. But as discussed below, the conventional neoclassical models are inadequate when analyzing STEM labor markets.

Spot Shortages

One can find, even by the neoclassical arguments based on supply and demand, that domestic shortages exist in certain STEM fields at certain times. In the late 1990s, the unemployment rate for computer systems analysts and scientists was almost half that of professional specialty occupations. There was also significant wage growth in IT occupations in the late 1990s. From 1996 to 1997, earnings of computer programmers increased by almost three times as much as earnings of workers in professional specialty occupations. (Table 3.5) All of these trends pointed to spot shortages in the market for IT workers that were called out in reports by the Computing Research Association, the Information Technology Association of America, and the Department of Commerce.[145]

Table 3.5: Evidence of Information Technology Worker Shortage in the late 1990s[146]

Occupation	Unemployment Rate: 1997	Change in Earnings 1996-1997
All workers	4.5%	2.7%
Professional specialty occupations	2.1%	2.7%
Computer systems analysts and scientists	1.1%	3.0%
Operations researchers/systems analysts	1.4%	6.4%
Computer Programmers	1.6%	8.8%

In 2007–2008, prior to the most recent economic recession, some STEM occupations exhibited similar signs of spot shortages. While unemployment data by occupation is not available in the CPS, wage data do exist. Table 3.6 shows several STEM occupations for which wage growth far exceeded the all-workers and professional-worker averages: environmental scientists and geoscientists, chemical engineers, network systems and data communication analysts, industrial engineers, operations research analysts, mechanical engineers, and computer software engineers.[147] This rapid wage growth suggests spot shortages. There has also been media recognition of a shortage of nuclear scientists and engineers. Note that these shortages exist not be only at the occupation level but also in particular geographic locations (e.g. not enough computer software engineers in Silicon Valley).

Table 3.6: Spot Shortages for STEM Occupations, 2007–2008[148]

Occupation	Change in Earnings
All workers	3.9%
Professional and related occupations	3.0%
Environmental scientists and geoscientists	16.0%
Chemical engineers	9.6%
Network systems and data communication analysts	8.8%
Industrial engineers, including health and safety	7.2%
Operations research analysts	6.5%
Mechanical engineers	5.8%
Computer software engineers	5.1%

Spot shortages can be hard to address through education given the long lead times required to train STEM workers. Freeman refers to this as the “cobweb” problem as the supply of STEM workers today is dependent on the market conditions when they first began studying for their degrees.[149] This lead-time ranges from up to four years for bachelor’s recipients to longer for doctoral recipients. Thus, education policy changes made in response to shortages today will take many years to impact the labor market, at which point there may no longer be a shortage.

Overall Shortages

Most economists who argue that there is little evidence of overall STEM worker shortage are what are known as neoclassical economists. This school of economic thought examines the economy through the lens of price-mediated transactions conducted by rational actors in stable markets.[150] In their view, industries and occupations are largely the same, differentiated only by pricing. Among conventional neoclassical economists, Galama and Hosek, Freeman, Lowell and Salzman, and Teitelbaum all argue that there has been scant evidence of shortages in the S&E labor market over the last two decades.[151]

At first glance, their conclusion is correct: in recent history, U.S. employers have been able to fill most STEM jobs, at least to the point where dramatic wage increases and plummeting unemployment is rare. The people filling these jobs may be qualified or unqualified, in-field or out-of-field, from the United States or elsewhere, but they are available. Moreover, an equilibrium between supply and demand is achieved regardless of whether both variables are low (bad for the economy) or high (good for the economy). Thus, there is a lot of flexibility to keep supply and demand in balance. However, the follow-on conclusion that somehow we have an "optimum" or even "adequate" supply—that the outputs of our domestic education system are nicely meeting the input requirements of our domestic workforce system, or that the U.S. workforce system itself meets the needs of an innovation economy—would be inaccurate.

Wages

Perhaps the statistic most often cited by the STEM shortage skeptics is the lack of overall wage growth for STEM occupations. For the neoclassical skeptics, this is an indicator that supply and demand are in balance. Indeed, since 1983, wage growth for STEM occupations has tracked that for all occupations as a whole, increasing by about 3.4 percent on average annually. (Table 3.7) Galama and Hosek argue that this indicates there is no sign of a shortage as "wages have not been increasing rapidly relative to trend."[152]

The problem with the neoclassical model is that it assumes that average wage increases mean no shortage, when it could just as easily be a reflection of a shortage that is addressed in a global marketplace.

But this conventional view assumes that wages are set in national and not international markets. It is true that for many occupations where workers are predominately employed in non-traded industries (e.g., law, health care, retail, trucking, government, etc.) shortages often lead to faster-than-average wage increases as employers bid up wages to attract a scarce supply of workers. But for occupations with workers predominately employed in internationally traded industries (e.g., computers and software, chemicals, pharmaceuticals), demand and supply factors are at least partially influenced by global, as opposed to domestic market conditions. In these occupations, shortages in workers may not lead to higher wages, for the globally competitive conditions in the industry may limit companies from paying higher wages, especially if many of their competitors are in low-wage nations. In the cases of shortages, firms may simply see positions unfilled with no above-average wage increases, or they may fill those positions overseas. The problem with the neoclassical model is that it assumes that average wage increases mean no shortage, when it could just as easily be a reflection of a shortage that is addressed in a global marketplace. And we see this differential in the wage increases for different professions. In professions such as law and medicine, in which licensing and the location-specific nature of work reduce vulnerability to foreign competition, wages increased faster than for STEM jobs, which are more exposed to international competition. (Table 3.6 and Figure 3.24)

Table 3.7: Changes in Median Weekly Earnings by Occupation, 1999–2009[153]

Occupation	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Average Annual Change 1983–2009
All workers	5%	5%	3%	2%	2%	3%	2%	3%	4%	4%	2%	3.4%
Professional specialty occupations	5%	4%	2%	3%	-4%	4%	2%	3%	2%	3%	1%	3.4%
Engineers	5%	6%	3%	2%	4%	1%	3%	4%	5%	3%	-2%	3.3%
Mathematical and computer scientists	5%	1%	8%	2%	-4%	6%	2%	3%	5%	1%	1%	3.3%
Natural scientists	5%	5%	-2%	7%	-4%	9%	3%	-1%	13%	0%	5%	3.4%
Physicians	10%	5%	-8%	20%	-5%	18%	-7%	4%	-8%	17%	0%	4.2%
Lawyers	-3%	11%	7%	8%	5%	0%	3%	7%	-8%	10%	0%	4.2%
Financial managers	3%	10%	6%	-5%	3%	-2%	8%	2%	-1%	5%	1%	3.4%

Figure 3.24: Median Weekly Earnings by Occupation, 1983–2009[154]

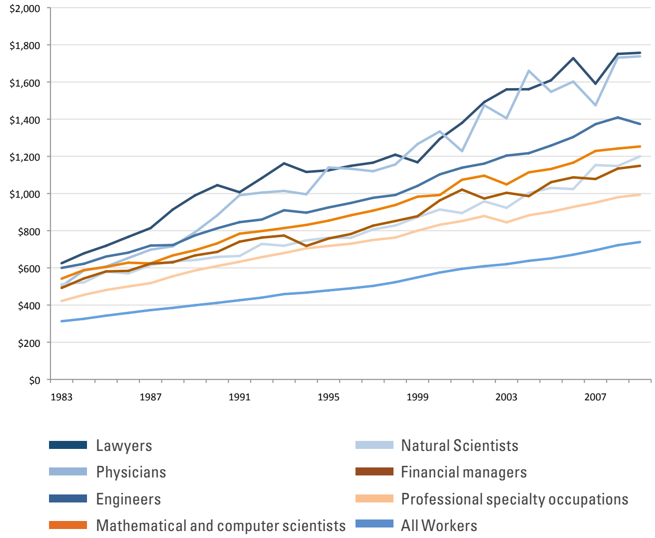
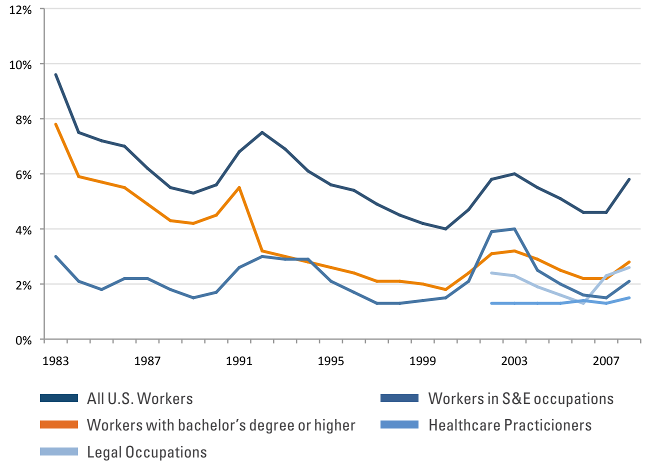


Figure 3.25: Unemployment in S&E Occupations vs. Other Occupations, 1983–2008[159]



There is a second, equally fundamental problem with the neoclassical explanation. If a shortage is defined as a shortage of Americans going into STEM fields, then the shortage looks much worse than if it is defined as a shortage of all workers, including foreign workers. Indeed, shortages of U.S. STEM workers spurred more STEM worker immigration to the United States. But as we discussed above, expecting to be able to rely on a strong pipeline of highly talented foreign STEM workers is a risky long-term strategy at best.

Unemployment

Some neoclassical economists also examine unemployment rates for STEM workers to make the "there is no shortage, overall" argument. Galama and Hosek argue that "unemployment has not been decreasing but has been steadily low, as is typical in professional occupations."[155]

But upon close examination of the data this argument does not appear to hold up. As Figure 3.25 shows, the STEM unemployment rate is not only low, but lower than that of workers with bachelor's degrees through all but about 5 years of this 25 year period. Frictional unemployment—a temporary unemployment of several days duration that results from transitioning between jobs, or getting settled into a new job after graduation—is typically about 2 percent to 3 percent and likely to account for most of the STEM unemployment most of the time.[156] Professions such as nursing, which have substantial shortages, still have unemployment rates that do not dip below 1 percent for this reason.[157] Frictional unemployment beyond 1 percent is expected to occur for any profession in which the time to match an employee to a job exceeds the Bureau of Labor Statistics' one-week definition of "unemployment." If it takes twice as long to match a (more specialized) engineer to a job opening, than it does a (more generic) nurse, this would account for 2 percent STEM unemployment, i.e., somewhere between half and all of the observed unemployment in the STEM curves, depending on the period. This is consistent with the 2 percent to 3 percent frictional unemployment seen for most jobs most of the time.[158] Thus, it does not appear that unemployment for STEM workers could get much lower; hence, there do appear to be the possibility of shortages.

In fact, it is actually somewhat remarkable that the unemployment rate for STEM professionals has been as low as it is—at 1.5 percent to 3 percent, except for the dot-com crash—considering workers from around the world come to fill STEM jobs in the United States. This is distinct from the situation for law or medicine (the lowest curves in Figure 3.25), where licensing requirements limit work to those already in the United States (or at least, those who have taken the U.S. licensing exams). What saves the U.S. STEM worker from suffering higher unemployment due to the influx of immigrants is that the immigrants are often complements to, rather than substitutes for, the skills of U.S. STEM workers. However, this fact also highlights the problem we have with structural mismatches between the skill set of our own citizens and those needed by U.S. employers. More accurate training to match skills to jobs would provide additional opportunities to U.S. STEM workers. It would also eliminate the residual amount of structural unemployment that currently prevents STEM workers with out-of-date skills or skills in fields undergoing major transitions, from finding jobs.

Degrees Granted vs. Job Vacancies

A final argument often made against shortages in the STEM workforce is that there is an excess supply of STEM graduates relative to the number of new STEM job openings each year. Comparing the number of graduates to new jobs, Lowell and Salzman argue that "the education system produces qualified graduates far in excess of demand: S&E occupations make up only about one-twentieth of all workers, and each year there are more than three times as many S&E four-year college graduates as S&E job openings."[160]

There are several problems with this analysis. First, as with the indicator of unemployment and wage rates, the indicator of graduates to jobs is misleading. The "new jobs" calculated by Lowell and Salzman include only the difference between total jobs (employed workers) one year versus the prior year. In other words, they assume a replacement job rate of zero (i.e., no one is retiring or leaving the workforce to raise children). In reality, replacement job openings number twice as many as new job openings, for most occupations most of the time.[161] Thus, the total number of available STEM job openings is likely to about 3 times (2 plus 1) the Lowell and Salzman number, or close to the number of graduating students.

Second, many people graduate with STEM degrees with no intention of entering STEM fields but instead plan on using core technical skills in other domains. Others graduate with STEM degrees but find that they prefer other occupations because of the nature of the work itself. These individuals are lost to the STEM job market and end up being replaced though immigration.

Third, the same result could occur if there was a shortage. If firms in the United States believe that there are not enough qualified STEM graduates coming into the marketplace, they could expand their output overseas, employing STEM workers there. In fact, they appear to have done this. With regards to R&D outsourcing, the largest shifts in R&D investment by U.S. companies were to China, Mexico, and South Korea, which have annual growth of R&D as a share of GDP of 160 percent, 129 percent, and 55 percent respectively. In contrast, R&D as a share of GDP actually declined 5 percent in the United States between 1999 and 2006.[162] Thus, it can appear that the demand for STEM workers was not growing much faster than STEM degrees because the demand was occurring in other nations. In other words, hearkening back to the French economist Jean-Baptiste Say, there may be a "Say's law" function occurring here, where supply of R&D creates demand for STEM workers and lack of STEM worker supply restrains demand (R&D investment).

One way to view the relationship between STEM supply and demand is to imagine that the United States has but two tiny solar companies and exactly the right number of solar engineers to staff them. However, around the world, dozens of much larger solar companies are aggressively looking for tens of thousands of employees because the industry is growing so rapidly. If we rely on national measures of unemployment rate or salary growth to tell us whether we have a shortage of STEM workers in solar, the answer will be no. Our tiny (national) supply is exactly equal to our tiny (national) demand. But we will be missing an enormous opportunity to participate in a lucrative, emerging market globally. We should, in this situation, be producing more STEM students capable of entering the solar industry, actively negotiating with other countries to establish standards-setting and market-entry opportunities, establishing research consortia to link our two companies with leading foreign companies to pull our students into the global marketplace, and taking other measures that proactively propel us into this growth industry, even though, by local measures, "there is no demand." In this regard, many of the emerging technology opportunities for the United States will be global. Relying on U.S.-only indicators of supply/demand mismatch will blind us to these opportunities.

Thus, in the new global innovation economy we are likely never to see the sharply rising salaries or gross over-employment rates expected by neoclassical economics even when STEM jobs are booming. This is because the United States is not a closed system, but part of a larger global system. Even now, U.S. STEM jobs are growing but foreign workers are filling some of them. We could capture these jobs for American workers if enough American workers gained the skills needed for these jobs and wanted to work in them. That is what the remainder of this report is about.

NEW INDICATORS OF STEM SUPPLY AND DEMAND MAY BE NEEDED

If the standard indicators of salary growth and unemployment rates are not the best metrics for assessing whether we need more STEM workers, what are the best metrics? One answer might be the length of time it takes companies seeking to hire STEM workers to find the right worker. This kind of information is now available via online job board aggregators, such as Wanted Technologies.[163] Long delays typically mean not enough workers exist, or the company had to go out-of-field or out-of-country to find a suitable worker, because the nominally available workers did not have an appropriate skill match. A particularly damning indicator would be long time periods for open-job announcements combined with short periods of employee tenure (high turnover). This would indicate that companies were desperately looking for people but unable to find the right worker; thus, they took whomever was available, even individuals who were grossly unqualified.

Another useful indicator is global job growth in a given sector. If the world's job base in a given sector is growing, and the United States wants a stake badly enough to commit to demand-side policies (e.g., R&D tax credits, international trade agreements, acquisition programs), then the production of more students/workers in this area makes sense. Note this is very different from the current practice of using BLS projections to estimate worker demand, because the BLS projections look only at the U.S. supply/demand dynamic. Ideally, we would have global projections from which promising sectors are identified and market-capture strategies are initiated by the U.S. government.

We can also look to the U.S. position in the global job market, relative to other countries, to understand where our workforce needs are. If a global sector has been stagnant, but the U.S. share of global jobs in that sector is trending upwards, then adding additional resources such as capital, students, and research would likely propel further expansion and increase U.S. market share. But what if the U.S. position was less clear-cut? In many sectors, the United States once had a significant share of jobs, but now that lead is eroding. In such cases, absent changes in other policies, the United States should look for subsectors (e.g., advanced manufacturing within manufacturing) in which its global share of jobs is not declining, and train students and create demand-side policies to support and grow these industries in the United States.

> **If the standard indicators of salary growth and unemployment rates are not the best metrics for assessing whether we need more STEM workers, what are the right metrics? One answer might be the length of time it takes companies seeking to hire STEM workers to find the right worker.**

There are also circumstances when the government should not invest in training more students. For example, even when sectors are booming in the global economy, if the United States has no demand-side policy, such investments are uncalled for. A case in point was the U.S. nuclear energy industry in the 1980s and 1990s, when it made little sense to train more nuclear engineers because policies and other factors limited the growth of the industry domestically. In other words, the STEM worker production issues (supply) cannot be separated from issues of demand. In addition, growth policies are not needed when a global sector declines for permanent structural reasons such as the replacement of horse and buggy companies by car manufacturers, or the replacement of typewriters by computers. Nonetheless, to understand where opportunities lie, we need to much more clearly articulate how many global jobs there are in a given sector, what the U.S. share is, and whether there is a demand-side policy dedicated to growing that share. As we shall see in later chapters, part of that demand-side policy will be nurturing the people who specialize in creating jobs, a key neglected component of the STEM workforce.

CHAPTER 4:

The Failure of the Prevailing "Some STEM for All" Approaches to STEM Policy

America's global share of STEM-focused activity is in decline, jeopardizing its status as the world's leader in innovation.[164] Moreover, as discussed in Chapter 3, there is clear evidence that the United States is not producing enough STEM graduates, especially of American citizens and permanent residents. And while increases in the quantity and quality of U.S. STEM workers will not by itself solve the problem of declining U.S. innovation competitiveness, it is an important component of a larger national innovation strategy. Consequently, there is increasing concern over how to get more Americans students to have stronger STEM skills and go into STEM fields.

For the past several decades, the proposed solutions to this challenge have been based on the "Some STEM for All" approach. The central tenant is that we can increase the quantity of STEM workers by reaching out to more students, more often, and with higher quality STEM education. The policy recommendations that embody the "Some STEM for All" philosophy additionally assume that institutions will change on their own, once they see the light and/or are given enough resources. Therefore, simply telling institutions what to do, and giving them money to do it, are the primary policy mechanisms, and the target audience is always "everyone."

The "Some STEM for All" approach towards increasing STEM-qualified workers is to make sure that every high school graduate and a much larger share of college grads become proficient in STEM.[165] Interventions at the K–12 level based on this approach include strategies such as boosting K–12 teacher quality (e.g., increasing teacher pay, requiring higher STEM teacher qualifications), more rigorous STEM standards (e.g., expanding requirements for STEM courses, more rigorous testing and assessment), improving curriculum, and boosting awareness among students of the importance and attractiveness of STEM careers. As an example of this approach it useful to look at the recommendations from a recent convocation of STEM educators in California.[166] Four "big ideas" emerged:

- Mandate Instructional Time for Science in Grades K–8
- Develop "Targeted" Professional Development for Teachers
- Switch to National Science Standards and Assessment
- Improve Public Perception of Science and Science Careers

These recommendations are all in the "Some STEM for All" category: expose all kids to more science teaching from better teachers and hold everyone accountable for results, all the while convincing everyone that science is important and rewarding.

The "Some STEM for All" approach is driven by a number of prevailing ideas. One is that since STEM is so important, and provides high-paying jobs, it is not fair that some socioeconomic groups, such as African Americans, Hispanics and women are underrepresented in STEM jobs. Moreover, these groups are often cited as untapped resources which could help increase the supply of STEM workers in times of need.[167] There is no doubt that women and minorities are underrepresented in STEM occupations and have been for quite some time. The question is whether we will ever enter a "time of need" in which these resources need to be drawn upon so heavily that K–20 institutions will go through the effort of reconfiguring themselves to allow a greater influx to occur.

The "Some STEM for All" approach is also driven by the view that boosting STEM education for all is critical to improving scientific literacy. In their book *Unscientific America*, Mooney and Kirshenbaum argue that U.S. citizens lack fundamental STEM knowledge, which leads to both a lack of students prepared to study STEM and a lack of a well-educated electorate prepared to make decisions regarding complex technical issues. They note:

> … for every five hours of cable news, less than a minute is devoted to science; 46 percent of Americans reject evolution and think the Earth is less than 10,000 years old; the number of newspapers with weekly science sections has shrunken by two-thirds over the past several decades. The public is polarized over climate change … and in dangerous retreat from childhood vaccinations. Meanwhile, only 18 percent of Americans have even met a scientist to begin with; more than half can't name a living scientist role model.[168]

Given this sorry state of affairs, the argument is that everyone should have higher STEM literacy since lack of knowledge purportedly leads to a lack of interest, which then leads to a lack of preparation for STEM careers. As the *Gathering Storm* report argues:

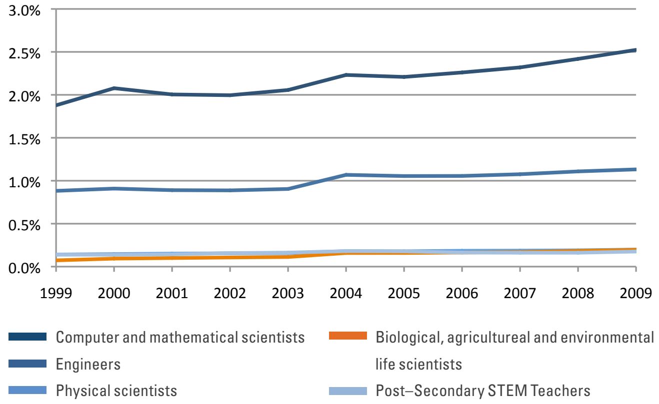
> Without basic scientific literacy, adults cannot participate effectively in a world increasingly shaped by science and technology. Without a flourishing scientific and engineering community, young people are not motivated to dream of "what can be," and they will have no motivation to become the next generation of scientists and engineers who can address persistent national problems, including national and homeland security, healthcare, the provision of energy, the preservation of the environment, and the growth of the economy, including the creation of jobs.[169]

As a result of the pervasive "Some STEM for All" perspective, some of prevailing policy solutions have been based on a misdiagnosis of the problem, thereby leading to proposed solutions that will not likely produce the needed expansion of domestic STEM college graduates who want to work in STEM jobs. Moreover, much of what is proposed involves significant investment, which in an era of fiscal constraint, has not been made and is not likely to be committed. And recommending that educational institutions do "the right thing" has not worked either, though this has not stopped the STEM policy community from persisting in the hope that if they just say it enough times, educational institutions will adopt more effective and enlightened approaches.

… the "Some STEM for All" formulation uses rhetoric that would suggest that unless every American knows calculus our economy will not be able to compete with the Chinese economy.

One reason why "Some STEM for All" is not the right formulation is that STEM jobs make up only approximately 5 percent of all jobs. (Figure 4.1)[170] Clearly, to power the innovation-driven U.S. economy, the vast majority of workers do not need STEM degrees. What is needed, however, is a modest increase in high-quality STEM workers. But the "Some STEM for All" formulation uses rhetoric that would suggest that unless every American knows calculus our economy will not be able to compete with the Chinese economy.

Figure 4.1: STEM Workers Share of Total Jobs by Occupation, 1999–2009 (in thousands)[171]



WHY HAVEN'T "SOME STEM FOR ALL" APPROACHES WORKED?

As discussed earlier, the "complexity view" of public policy intervention suggests that systems like the production and demand for STEM talent are not simple, mechanistic systems where pouring more resources in at the front end leads to more outcome at the back end. Rather, they are complex systems with multiple actors having different motivations, multiple feedback loops, uncertainty, and a host of other complex factors, such that simple and "obvious" solutions are not always the right ones.

In contrast to this, the mechanistic model behind the "Some STEM for All" approaches is simple and linear: the "leaky pipeline." The leaky pipeline has become the iconic representation for the national production of scientists and engineers from young students. Indeed, this model has been the basis of multiple reports.[172] The pipeline is presumed to be linear and completely open from end to end, but with leaks along the way where potential candidates "drop out." As a greater number of STEM-qualified individuals defect at each stage of education and career, fewer are left to enter the next stage. Norm Augustine, chair of the National Academies *Committee on Prospering in the Global Economy of the 21st Century*, describes the leakage succinctly in a recent essay:

> As one might suspect, there is a great deal of leakage along that extended educational highway. To begin with, about one-third of U.S. eighth-graders do not receive a high school diploma. And of those who do, about 40 percent do not go on to college. About half who do begin college do not receive a bachelor's degree. Of those who do receive such a degree, two-thirds will not be in science or engineering. And of those who are U.S. citizens and do receive degrees in either science or engineering, only about 1 in 10 will become candidates for a doctoral degree in those fields. And over half the doctoral candidates drop out before being awarded a PhD.[163]

While appealing, this leaky STEM pipeline model is problematic, first and foremost, because it suggests that the central problem is one of sheer quantity of inputs.

While appealing, this leaky STEM pipeline model is problematic, first and foremost, because it suggests that the central problem is one of sheer quantity of inputs. As Augustine notes, "The point is that it takes a lot of third-graders to produce one contributing research scientist or engineer and a very long time to do it."[164] In other words, if everyone has an equal probability of taking the next step to become STEM-educated, then the best way to get more at the end of the pipeline is to put a lot in the beginning. But as described below, this does not appear to be accurate.

But there is a second problem with this view: even if the "fill the pipe" model were successful, it requires a tremendous amount of resources to keep the pipe full. A way to understand why is to consider another profession that employs a relatively small percentage of adults (albeit much smaller than in STEM): professional basketball. Imagine if there were a shortage of basketball professionals. The leaky pipeline/"Some STEM for All"model would respond by increasing basketball courses at each grade level from K–12, paying basketball coaches more, ensuring that they were certified, and penalizing schools that had losing seasons. At the end of the day, the reality is that few people are interested in playing basketball at the professional level and a much smaller number have the ability to do so. It takes a combination of factors, including but not limited to a high level of athleticism (and usually height) and an interest in sports. STEM is no different. Not everyone is interested in STEM, no matter how attractive the field is. Not everyone has the capability to get a STEM degree, no matter how good their teachers are or how many STEM courses they are required to take. And not everyone has the personality characteristics leading them to want to be a STEM worker. And to be clear, we are not saying that these differences in interest or capability are related to race, sex, socio-economic status, or other such factors. But nonetheless, the differences are real.

Despite its fundamental flaws, the leaky pipeline model has persisted. Based on the linear mental model, many have concluded that deficiencies in both quantity (and even quality) can be overcome by "fattening the pipeline" at an early stage—e.g., there would be more STEM workers if only there were more college students majoring in STEM; there would be more college students majoring in STEM if only there were more high school students taking the necessary math and science courses; there would be more math-capable high school students if only there were more middle-schoolers taking algebra. And so on.

The leaky pipeline/"Some STEM for All" approach underlies many major STEM reports. The heralded National Academies' report *Rising Above the Gathering Storm* lists improving K–12 science and math education as one of its central recommendations, with the goal of increasing the size of America's STEM talent pool. Indeed, their first recommendation is "Increase America's talent pool by vastly improving K–12 science and mathematics education." They go on to state: "The U.S. system of public education must lay the foundation for developing a workforce that is literate in mathematics and science, among other subjects."[175] More recently, the National Science Board recommended similar improvements to K–12 STEM education, with an emphasis on improving the skill set of all American students:

> The National Science Board recommends a set of actions for the new Administration to implement starting in early 2009 to advance STEM education for all American students, to nurture innovation, and to ensure the long-term economic prosperity of the Nation.[176]

It is clear that the central agenda of the STEM policy community is to "fatten" the STEM pipeline at an early stage by improving the general science and mathematics proficiency levels of the nation's K–12 students. While there is no doubt that improving math and science skills has value, we should consider the possibility that other issues exist that prevent "Some STEM for All" programs from being effective in delivering a high performance STEM workforce.

An Expanded Pipeline Does Not Necessarily Result in Improvements to the Quantity or Quality of STEM Student

The pipeline model assumes that increasing the number of candidates at an early stage will inevitably result in human capital spillover to the subsequent stage. It also assumes that by "fattening" the candidate pool at each stage, the talent level of each subsequent stage will improve, or at least hold constant. Further, it assumes that the gating mechanisms—the "valves" that regulate the flow from one part of the pipeline to the next—are effective. To stay with this analogy, replacing a malfunctioning valve is likely to be a more effective, and much cheaper strategy, than increasing the size of a five-mile-long pipe.

The first assumption is violated in any situation where gates remain at constant size, or do not increase proportionately to the increases in the size of the pipe. If these gates are not addressed, efforts to increase the quantity of capable K–12 students will not lead to commensurate increases in the quantity of B.S. students or STEM-qualified workers. An example might be enrollment limits on undergraduate engineering classes. If more students with strong STEM credentials are admitted to the school, but enrollment limits on STEM classes are not changed, the number of graduating B.S. engineers also does not change. Other examples are discussed below.

The second assumption is that the gates that exist in the STEM pipeline are at least neutral towards the quality of the individuals passing through. However, gating mechanisms often do not select for the best candidates. The criteria for selection can be critically misaligned with the desired skill set; often, reliable metrics for the desired skill do not even exist. If we wish to move towards a STEM workforce of the "best and brightest," we must implement gating mechanisms that reliably reward higher skills, independent of other applicant attributes. In short, when the means of advancing along the pipeline are skewed and misaligned, the later stages do not readily benefit from size increases in the preceding candidate pool.

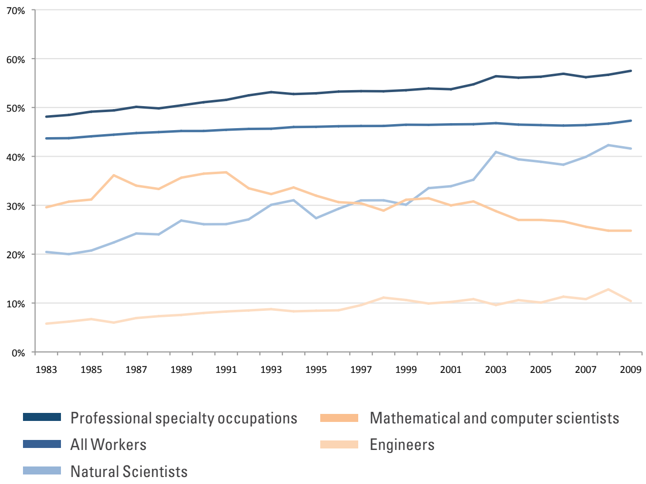
Gating Mechanisms Limit Quantity

When gating selects for attributes unrelated to skill, it tends to reduce the pool size without changing quality. This situation appears to be the case for defections from STEM during college. In their book, *Talking about Leaving*, Seymour and Hewitt chronicle the characteristics and numbers of individuals who leave the STEM pipeline during college, and compare these data to the characteristics of individuals who stay in STEM.[177] A key finding is that individuals who leave the STEM pipeline during college have about the same GPA as those who stay (and the women who left had an even higher GPA than men who stayed). Thus, the gates are effective at reducing pool size, but contrary to the popular image of "weed-out courses," curricular gates are neutral for quality. Ideally, to the extent we want a gating system, we want one that selects for quality, rather than one that is neutral to it.

> **... that individuals who leave the STEM pipeline during college have about the same GPA as those who stay (and the women who left had an even higher GPA than men who stayed).**

Below we summarize examples of pool size reduction via gating mechanisms that come from the women's discrimination literature. Women are underrepresented in STEM. While women occupy 60 percent of all professional specialty occupations, which are inclusive of all STEM occupations, women are underrepresented in all STEM occupations, with a low of 10 percent representation in engineering in 2009. (Figure 4.2)

Figure 4.2: Female Representation in STEM Occupations, 1983–2009[178]



Changing the gate can have an almost immediate impact on the characteristics of the resulting outflow, including increasing the participation of women in STEM. Changing a gate is faster, cheaper, and more effective than a "Some STEM for All" supply-oriented solution. Changing the gating mechanism, and not the supply, was the answer to increasing female representation among winners of the National Institutes of Health's Pioneer Award, instituted in 2004 as a major grant for individuals distinguished in their field. In the first year of the Pioneer Award program, all of the awardees were men.[179] By the next year, 46 percent of the awardees were women. What changed? First, the opportunity was advertised much more broadly, so its availability was not limited to the "in crowd." Second, the award no longer required that one be nominated by a colleague—a process that largely resulted in established males recommending their friends. Instead, the applicants were self-nominated. And, finally, the representation of women on the judging panel was increased from 4 percent to 44 percent.[180]

Student works with her professor at Carnegie Mellon University.

A second example, the remarkable increase in female computer science students at Carnegie-Mellon University (CMU) from 7 percent to 42 percent between 1995 and 2000, was attributed in significant part to the redesign of admissions criteria.[181] CMU decided not to weigh prior experience in computing as heavily as it had in the applicant selection process after it was determined that such experience had little impact on a student's future success. In addition, a wider variety of attributes, such as leadership potential, were used to evaluate candidates. These changes resulted in a class makeup that was far more diverse than in earlier years, but with the same median test grades and scores.[182]

STEM is not the only profession where gates occur. Orchestras, for example, have long been dominated by male instrument players, in part because auditions were historically nepotistic and based on small audition classes.[183] Less than 10 percent of orchestra new hires were women, prior to 1970. In the 1980s, two changes were implemented that ultimately resulted in the major orchestras hiring women among new applicants at a rate of 35 percent to 50 percent.[184] The first was a much broader and more public advertising of the positions, rather than the historical word-of-mouth from male music directors to their circle of (male) friends. The second was a new practice of "blind auditions," wherein the applicant's identity was hidden from the judges by a screen. These two changes alone are credited for about 66 percent of the improved hiring of women. By the 1990s, the major orchestras contained between 20 percent to 30 percent women.[185]

These examples show that changing the gate characteristics can change the composition of the individuals in the outflow, almost immediately. However the above examples are ones in which the traditional gates actively screened out individuals based on factors not relevant to the skills being sought. More dangerous, perhaps, are gates that consistently and selectively screen against the best talent. In STEM, these are often gates that promote willful defection of talent out of STEM fields.

Gating Mechanisms Limit Quality

Research suggests that our top achieving STEM students are vacating the pipeline at increasingly high rates at the high school, collegiate, and early-career levels.[186] Norm Augustine highlights the defection rate of talent at the post-degree level, noting their relative success in competing industries:

> Furthermore, even after they receive their degree, a growing proportion of U.S. graduates—in the case of baccalaureate engineers, slightly over half—decide to become investment bankers on Wall Street, lawyers, corporate executives, or some other form of worker.[187]

In some cases, the attrition may be due to the attractiveness of the alternative career paths. Enrollment in science and engineering graduate programs showed a steady increase from 1984 through 1994, followed by a decline from 1995 to 1999.[188] Since 2000, there have again been gains, peaking with 619,499 enrollees in 2007 (the last available year of statistics).[189] The period of decline, 1995 through 1999, corresponded to a period in the American economy known as the "technology bubble" or "dot.com bubble." This era bore a plethora of opportunities for technologically savvy workers, as evidenced by the corresponding jump in initial public offerings, for information and communications technology (ICT).[190]

These data suggests that many young, well-educated students were choosing to work in the ICT field rather than attend science or engineering graduate school. This relationship was noted in *Rising Above the Gathering Storm*:

> Where are the top U.S. students going, if not into science and engineering? … Some seem attracted to MBA programs, which grew by about one-third during the 1990s. In the 1990s, many science and engineering graduates entered the workforce directly after college, lured by the booming economy. Then, as the bubble deflated in the early part of the present decade, some returned to graduate school.[191]

Alternatively, they could have chosen law or medicine; between 1990 and 2000, salaries increased more quickly for lawyers and doctors than for Ph.D. scientists.[192] Notably, the mid-1990s' drop in enrollment aligns perfectly with the aforementioned observed trend in education: highly talented (upper quintile) students defecting from STEM-centric career paths.[193]

The Pipeline is Choked with Gates

In conclusion, there are two types of gates that prevent "Some STEM for All" approaches from working well. There are gates that select for attributes unrelated to quality, which blindly reduce quantity with no impact on quality. Some examples are admissions, applications, and selection criteria for which a de facto requirement is having social connections in the field—the early NIH Pioneer rewards are an example of this—but other examples abound throughout this report. There are also gates that select against quality, such as the relatively poor financial rewards offered by fellowship programs as inducements to pursue STEM Ph.D.s. Both types of gates negatively impact the human capital gains across all "Some STEM for All" approaches.

Getting 5 percent of the workforce to be STEM-proficient does not require STEM education for everyone, everywhere, all the time. Focusing on fewer individuals allows the luxury of building a "new and improved" pipeline that emphasizes mass customization of content, development of innovation-era (rather than production-era) skill sets, and frequent industry engagement with the application and practice of those skills.

Because the pipeline is choked with gates, and because we only need to boost STEM grads by a few percentage points (along with improving STEM graduate quality), in order to address the challenge facing the nation, we advocate a strategy of accurately targeting and recruiting STEM talent from all domestic sources and pulling this much smaller group through a "new and improved" pipeline that avoids common gates and delivers the best educational experiences STEM has to offer. To go back to our basketball analogy, rather than requiring basketball clinics, directing more money to coaches and adopting other expand-the-pipeline strategies, basketball works by actively targeting and pulling the most promising kids and then young adults through the pipeline, and by creating specialized experiences to help them thrive.

While the "Some STEM for All" efforts are well-meaning, they often fail to provide the kinds of opportunities needed by underrepresented groups to excel in STEM. In contrast, more innovative and specialized efforts, like the Dallas School of Science and Engineering, one of the best STEM high schools in the nation, enable underrepresented minorities to excel at STEM.

This "All STEM for Some" approach is far more cost effective than "Some STEM for All" because of the smaller number of individuals involved. Getting 5 percent of the workforce to be STEM-proficient does not require STEM education for everyone, everywhere, all the time. Focusing on fewer individuals allows the luxury of building a "new and improved" pipeline that emphasizes mass customization of content, development of innovation-era (rather than production-era) skill sets, and frequent industry engagement with the application and practice of those skills.

Some will object that the "All STEM for Some" is not a meritocracy comparable to that of the "Some STEM for All" solutions currently being implemented. In fact, it is likely to be more meritocratic than the current system or even the ideal system envisioned under the "All STEM for Some" proposals. While the "Some STEM for All" efforts are well-meaning, they often fail to provide the kinds of opportunities needed by underrepresented groups to excel in STEM. In contrast, more innovative and specialized efforts, like the School of Science and Engineering Dallas, one of the best STEM high schools in the nation, enable underrepresented minorities to excel at STEM. They target the young people who are most interested and passionate about doing well in STEM. In short, the key to making "All STEM for Some" work is an accurate and aggressive national recruiting effort that transcends racial/ethnic/income/gender/school boundaries, much as NCAA basketball does for sports.

LIMITATIONS OF CONVENTIONAL APPROACHES TO K–12 STEM EDUCATION

Understanding that the pipeline model ignores complexity and is choked with gates, we now look at three of the "Some STEM for All" solutions that have dominated conventional thinking over the past two decades. Below, we discuss specific pitfalls in such strategies as increasing public interest in science, improving the subject matter expertise of teachers, and aligning/standardizing STEM curricula.

Does Improving Public Interest in Science Improve Student Participation in STEM?

Relative to other countries, the United States graduates a lower percentage of students with science and engineering degrees. Of American 24-year-olds with a college degree, only 15 percent have received theirs in the natural sciences or engineering (versus 50 percent and 67 percent, for China and Singapore, respectively).[194] Of the 17 nations surveyed in this respect, the United States ranked next to last. Some suggest that this trend reflects a culture that ignores, or even looks down on science. By paying little attention to scientific and mathematical accomplishment, American society presumably discourages its best students from pursuing STEM-related careers.

Reflecting this belief, prescriptions to improve the public stature of science and math are becoming increasingly common.[195] For example, the National Science Board's *National Action Plan 2007* states that the National Science Foundation "should continue to develop and fund programs that increase public appreciation for and understanding of STEM" and "should consider how its STEM outreach portfolio can be modified to provide more coherent public outreach on STEM and STEM education issues."[196] Similarly, John Holdren (Director of the White House Office of Science and Technology Policy) and Arne Duncan (Secretary of Education) recently underscored the need to "raise the public profile of science, engineering, and mathematics."[197]

Despite the prevailing belief of Americans' widespread disinterest in science, data from the National Science Foundation suggest otherwise.

But these claims ignore the fact that our culture is already as enthusiastic about science, if not more so than most others. Despite the prevailing belief of Americans' widespread disinterest in science, data from the National Science Foundation suggest otherwise. In one recent survey, 80 percent of Americans stated they were "very" or "moderately" interested in new scientific discoveries.[198] The results also suggest that most Americans recognize the practical benefits of science (68 percent agree the benefits outweigh the harm), and hold scientists in very high regard (ranking them second behind military leaders, in terms of public confidence).[199]

Overall, the optimism displayed by Americans for science and technology rivals (if not exceeds) that of China and

South Korea, while far outstripping that of Europeans, Russians, and the Japanese.[200] Taken as a whole, the data is suggestive of a culture that appreciates scientific achievement and values STEM-related education.

Overall, the optimism displayed by Americans for science and technology rivals (if not exceeds) that of China and South Korea, while far outstripping that of Europeans, Russians, and the Japanese.

If Americans do have an appreciation for science, then what are we to make of our students' reluctance to focus on and major in STEM? The data suggest that rising student disinclination to pursue STEM is not uniquely American, but rather endemic to industrialized nations. According to the Organization for Economic Cooperation and Development:

> The share of science and engineering graduates continues to fall … On average, 25 percent of the degrees awarded at universities in the OECD area in 2005 were in science-related fields (engineering, manufacturing and construction, life sciences, physical sciences and agriculture, mathematics and computing). However, the number and proportion of S&E graduates has changed markedly in recent years. In absolute terms, the number of students graduating in S&E increased, except in Germany … in Hungary … and in Spain. However, in relative terms, the share of S&E graduates decreased in 17 of the countries shown in Figure 1.37. The largest drop in the share of S&E graduates (around 3 percentage points or more) occurred in Ireland, Switzerland, Denmark, Iceland, the United Kingdom and Sweden.[201]

Yet, the report goes on to offer a conventional "Some STEM for All" solution: "In view of the declining share of S&E graduates in many OECD countries, these results suggest a role for government in terms of improving students' interest in science."[202] Similarly, policy experts in Europe and Asia lament youth disinterest towards STEM material, often proposing new programs to bolster interest.[203] For example, a 2004 report by the European Commission's *High Level Group on Increasing Human Resources for Science & Technology in Europe* (the existence of this organization suggests a problem, ipso facto) notes:

> For several years now there have been warnings from universities that the number of students has been declining sharply in certain disciplines, namely physics, chemistry and mathematics. In some countries, there seems to be increasingly pronounced evidence of a decline in young people's interest in studying science and retaining the option of pursuing science-related careers.[204]

A recent U.K. article, *Attitudes Toward Science: A Review of the Literature and its Implications*, notes:

> The increasing attention to the topic is driven by a recognition that all is not well with school science and far too many pupils are alienated by a discipline which has increasing significance in contemporary life, both at a personal and societal level.[205]

In Asia, the Japanese policy report *White Paper on Science & Technology 2008*, states:

> Many Japanese feel that science and technology make contributions to society, but their concern is declining, particularly among the younger generation … In the future, in order for S&T to keep growing and be accepted by society, it is important to continuously improve its levels to create intellectual and cultural values and also to enhance efforts to return the fruits to society.[206]

The fact that three disparate cultures—one Asian, one European, and one North American—are all experiencing similar difficulties suggests that the problem is not unique in cultural origin.

Student Interest in Developing Nations

Greater student participation in STEM does exist in economically-emerging countries, but can be traced in part to a lack of opportunities outside of STEM fields. It is instructive to note that the one country most often held up as a model for "student interest in STEM" is China. Yet in China, the enormous number of university degrees in science and engineering (911, 846 degrees in 2006, roughly 53 percent of all those awarded in China that year) is achieved by the Ministry of Education preferentially increasing the number of schools and degree programs specializing in STEM.[207] Since college admission is determined by a highly competitive national examination (the National Higher Education Entrance Examination, or Gaokao), and slots are in short supply, it has been possible to expand Chinese youth's participation in STEM fields just by enlarging the number of available seats in STEM while limiting seats in other non-STEM programs.[208]

The competition for higher education in China is intense, as suggested by the discrepancy between high school and college enrollments. According to the *China Statistical Yearbook 2006*, an average of 1,977 students were newly enrolled in "junior secondary schools" per 10,000 residents in 2005.[209] However, only 878 enrolled in "senior secondary schools," where the high-achieving students who plan on attending college subsequently go (the alternative is enrolling in the very large vocational/technical arm of the secondary school system). Hence, it appears that only 44 percent of students from junior secondary even get a chance to apply to college. Of those that make it to senior secondary school, only 505 out of 10,000 were newly enrolled in institutions of high education in 2005. This suggests that only 58 percent of students who have enrolled in senior secondary school (and just 26 percent of those who have enrolled in junior secondary school) will be able to attend college.

The discrepancy between the high percentage of S&E graduates in China and the low percentage of total graduates is noted by the OECD:

> China has the world's second largest stock of human resources for science and technology, just after the United States and ahead of Japan. Its share of university graduates with degrees in science and engineering is 39.2 percent, almost twice that of the OECD average. On the other hand, the overall level of tertiary attainment is still quite low, even by developing country standards, and the number of researchers per 1000 total employment is very low, at about one-tenth of the level of Finland, the world leader.[210]

In essence, the excess demand for a college education—any college education—drives desperate Chinese students to select those seats in STEM.

In the United States, it would not be possible to translate excess demand for college into increased demand for STEM education, both because the supply of college seats more equally matches the demand (at least, at the currently established price point), and because the government does not centrally control the establishment of degree programs or enrollment quotas. Hypothetically we could increase STEM enrollment significantly by withdrawing federal aid in support of humanities, social science, business and law programs in colleges, essentially forcing young people who want a college degree to get one in STEM. Of course we don't want to and shouldn't do that.

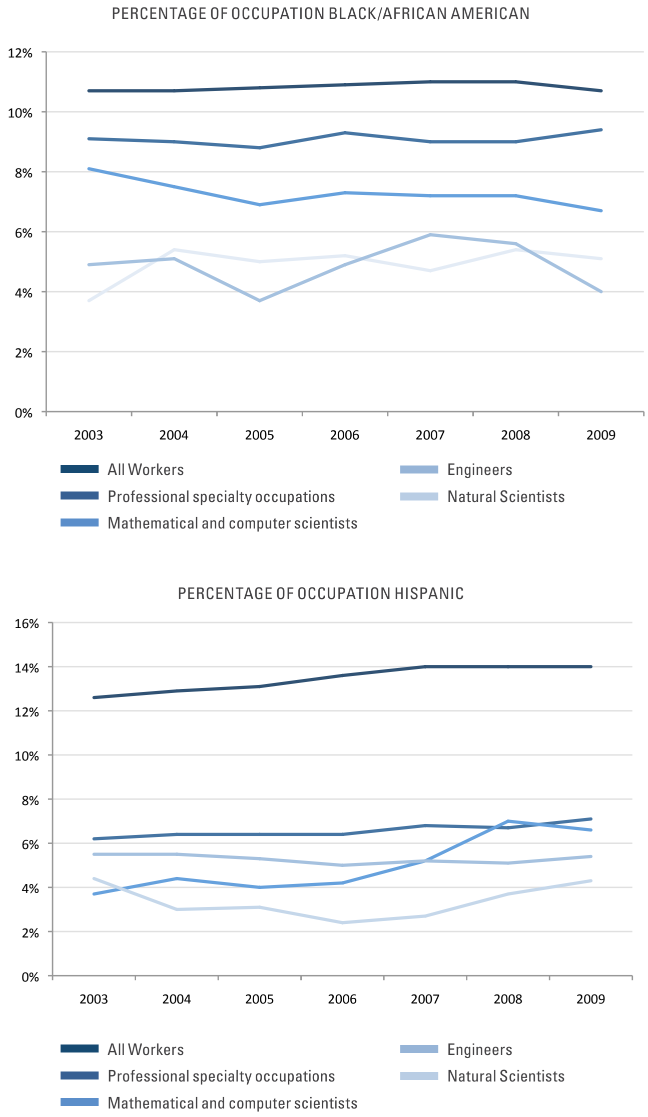
As such, we posit that systems like that of the United States, in which a student's ability to attend college or graduate school is independent from his choice of major, will never see double-digit-per-year STEM graduation increases like those seen in China (a 14.5 percent increase in first university degrees from 2005 to 2006, versus 1.8 percent for the United States).[211] Students everywhere recognize that science and mathematics courses can be difficult or taxing. Where they are given free choice (and a reasonably secure future outside of STEM), many will tend to select less demanding alternatives to STEM-heavy career tracks (despite having at least a moderate interest in the sciences).

Media Campaigns Can Change Public Attitudes, but Don't Necessarily Translate to Increased STEM Student Production: The "Math is Power" Story.

Because of the belief that our culture is indifferent to (or ignorant of) the value of STEM education, many have called for improved public awareness campaigns to reshape student interest and behavior. The notion goes that if only students were more aware of the benefits of STEM education significantly more would choose this path.

This approach has been used to address the lack of mathematical proficiency amongst American students generally,

Figure 4.3: Underrepresentation of Minorities in STEM Occupations, 2003–2009[212]



but was applied most vigorously to attempts to address STEM education gaps amongst underprivileged minority students (African-Americans, American-Indians, and Latinos). As illustrated in Figure 4.3, African-Americans and Hispanics are underrepresented in STEM jobs.

In 1994, a report by the National Action Council for Minorities in Engineering (NACME) found that only 6 percent of disadvantaged minorities were graduating high school with the requisite math needed for an engineering or related degree, versus approximately 15 percent for their nonminority peers.[213] The NACME surveys also indicated that students did not recognize the importance of math as a foundation for later achievement. Furthermore, they found that course selections were frequently being made without the assistance of counselors or parents.

In order to reverse these trends, NACME launched the 1995 public service campaign, *Math is Power*. As the campaign centerpiece, the program aired a series of targeted television advertisements emphasizing the importance of math to career potential (specifically, jobs with higher wages). In 1999, NACME repeated their 1995 survey to gauge the impact of the *Math is Power* program. Encouragingly, they found that the campaign had reached a significant portion of its target audience: "Half of all students surveyed are aware of the campaign, with a majority of them familiar with at least one of its key messages." However, the feedback on its impact was mixed, at best. While some areas showed marked progress (notably, an increase in favorable attitudes towards math), other critical areas showed little change:

> The disparity revealed in 1994 between students' expectations for their future careers and their current actions regarding the study of mathematics and science continues to exist … half of all students still plan to take math only as long as they are required to do so. Interest in college and the study of scientific subjects at the college level remains high, but students today are less likely to think that the decision to take math and science classes is an important one. They are also less likely to view math as important for their careers than they were six years ago … Unfortunately, a sizable proportion of all students continue to make decisions about the study of advanced math and science in a vacuum, devoid of adult support and appropriate information.[214]

The program was subsequently halted, in part due to its limited effectiveness. Taken as a whole, the results of the *Math is Power* campaign suggest that using mass media to reshape student attitudes may work, but the changed attitudes do not necessarily translate to changed behaviors.

Taken as a whole, the results of the *Math is Power* campaign suggest that using mass media to reshape student attitudes may work, but the changed attitudes do not necessarily translate to changed behaviors.

Efforts to Increase Teacher Quality do not Make a Significant Difference in the Production of STEM-Ready Students

Interest in improving the strength of the STEM pipeline at the K–12 level has inspired a number of suggestions from the policy community. Perhaps no aspect of the American school system has been more scrutinized than teacher quality. The pedagogical skill of the instructor is widely believed to be the key determining factor in student success both within and without STEM fields.[215] Consequently, the science policy field has strongly backed measures for improving the quality of K–12 STEM teachers with the hope of achieving better student outcomes (e.g., better test scores) in STEM subjects.[216]

But what pedagogical characteristics contribute to teacher quality? Few clear factors amongst teachers appear to correlate directly to student performance.[217] One quantitative analysis showed that only 3 percent of a "good" teacher's performance can be attributed to readily measurable aspects of the teacher: e.g., years of experience, education level, proficiency on tests. The other 97 percent of teacher performance lay outside of these readily quantifiable variables, in qualities such as enthusiasm, skill in relaying knowledge, intelligence, and the ability to relate to children.[218] For STEM, the evidence discussed below suggests that the relationship between paper credentials and teacher quality is only marginally higher, and then only in the case of mathematics, not science.

Subject Master Expertise is Often Seen as a Proxy for Teacher Quality

In the absence of clear measures of teacher quality, the STEM community has typically advocated using subject-matter expertise as a proxy. Many policy experts widely assume that teacher effectiveness correlates with formal training in their relevant field, generally in the form of an advanced degree. This expertise is particularly emphasized for STEM subjects, where expertise amongst middle and high school teachers is increasingly rare. The heralded National Academies' report *Rising Above the Gathering Storm* underscores technical expertise in the classroom as a key component of America's success:

> We need to recruit, educate, and retain excellent K–12 teachers who fundamentally understand

> biology, chemistry, physics, engineering, and mathematics. The critical lack of technically trained people in the United States can be traced directly to poor K–12 mathematics and science instruction. Few factors are more important than this if the United States is to compete successfully in the 21st century.[219]

Similar calls to increase the number of "in field" science and math teachers were made in the 2010 *Science and Engineering Indicators* report, which reiterated previous recommendations from the National Science Board:

> Adequate subject matter knowledge and skills are critical for teachers to teach their subjects well … NCLB mandates that all students be taught by teachers who not only are fully certified and possess at least a bachelor's degree, but also demonstrate competence in subject knowledge and teaching. In its 2007 policy recommendations regarding STEM education, the National Science Board emphasized that STEM teachers should receive adequate STEM content knowledge that is aligned with what they are expected to teach.[220]

As a whole, the STEM policy community has unequivocally embraced the notion that teachers must have some degree of in-field expertise, if K–12 STEM education is to improve.

However, educational research linking subject-matter expertise and teacher quality suggest at best a weak correlation, and at worst, no correlation at all. Just as importantly, improving subject matter expertise in all or most U.S. middle and high school teachers is an extremely expensive solution. The body of educational research does not on the whole support this route. In the contexts where a weak correlation between subject-matter expertise and teacher quality does manifest, its sharp diminishing returns imply that advanced degrees are not a cost-effective approach to improving K–12 STEM education.

For example, one recent analysis found no significant correlation between advanced degrees and teacher effectiveness in the subjects of math and reading. The study focused on data from the Florida public school system, grades K through 12, from 1999 to 2005. The researchers were able to track individual students and teachers, and linked each teacher to his/her respective college coursework. After correcting for classroom experience and in-service professional training, the data found little evidence linking teacher quality to advanced education:

> Like other recent work, we find generally positive, but mixed, evidence on the effects of experience and little or no evidence of the efficacy of advanced degrees for teachers … Only in the case of middle school math do we find that obtaining an advanced degree enhances the ability of a teacher to promote student achievement. For all other grade/subject combinations the correlation between advanced degrees and student achievement is negative or insignificant.[221]

The impact of subject matter degrees on student performance was also analyzed in a national study of 3,784 twelfth-grade math students and 2,524 twelfth-grade science students.[222] The results show that only about 8 percent of the standard deviation on student math test scores could be attributed to the teacher having an master's. degree in math, with results for bachelor's in math being similar. Teacher training in science showed far less of an effect, and actually a small negative effect for teachers with bachelor degrees in science.

Such results are not new; older educational studies have corroborated these findings. A 1984 literature review by the Government Accountability Office on federal aid programs for math and science teachers concluded that no clear relationship exists between expertise and teacher quality:

> However, research to date clearly has failed to show a straightforward relationship between a teacher's knowledge and the subsequent learning by their students in mathematics and science, at least for teachers in classrooms in the early 1970s. This finding challenges a common assumption—the belief that the more a teacher knows about the subject being taught, the better the teaching that will be done and the more the student will learn about the subject in question.[223]

However, a limited positive relation between advanced degrees and teacher quality was seen in a study by David Monk, who evaluated the math and science achievements of tenth-grade students from across the country, and compared those scores to the education levels of their respective math and science teachers. The resulting data, which relied on NAEP-designed exams to measure student progress, suggests that a teacher's formal education level correlates with higher scores, but has a sharp diminishing return (if not a threshold) on benefits:

> The findings suggest that teacher content preparation as measured by the number of courses a teacher took in the subject area being taught is positively related to how much mathematics and science students learn at the secondary level … As a broad generalization,

> teacher preparation makes a positive difference, though the nature of the relationship and the absolute magnitude of the positive effect varies. In particular, a number of the estimated relationships have non-linear natures and suggest the presence of either diminishing marginal returns or threshold effects.[224]

The marginal returns of the relationship led the author to suggest that advanced degrees might not be a cost-effective solution to teacher quality:

> First, we need to be mindful of how divorced these results are from the cost dimension of productivity analysis … Findings that measures of teacher subject matter preparation and knowledge are correlated with pupil performance are not sufficient by themselves to justify policies designed either to recruit or train more knowledgeable teachers for schools. The embodying of subject matter expertise in proximate teachers involves substantial cost, and these costs must be balanced against the magnitude of the gains … We need to keep in mind that many of the estimated relationships between teacher course preparation and pupil gains are by no means large in magnitude.
>
> Second, even if it is true that teacher subject matter knowledge is an important antecedent to student performance gains, it does not necessarily follow that social welfare is served by requiring prospective teachers to complete undergraduate majors in content areas followed by a fifth year of professional education study at the graduate level. There may be other more cost-effective ways of conveying the relevant subject matter knowledge to prospective teachers.[225]

In the end, we must recognize that teacher qualifications are not a substitute for teacher quality. Solutions that call for higher education levels of teachers underestimate the cost-to-benefit ratio of such programs.

In the end, we must recognize that teacher qualifications are not a substitute for teacher quality. Solutions that call for higher education levels of teachers underestimate the cost-to-benefit ratio of such programs. It may be that only 55 percent of all math teachers in the country have a B.S. in math, but another 21 percent have a B.S. with a math minor or a math 2nd degree, and fully 82.6 percent have state certification to teach math.[226] Thus, most math teachers already have substantial math training. Bringing all up to a B.S. level degree in math would require educating or re-educating 45 percent of all teachers, for what amounts to, at most, 8 percent[227] of a standard deviation's improvement in student performance (and much less for science).[228] For classes graded on a curve, this amounts to taking a C student and moving him less than 1 point up towards a B. And this enormous national expenditure, in the end, would only reach the 5 percent of children ultimately destined for the STEM workforce. By emphasizing the "on paper" qualities of teachers (and not their actual performance), we invest in a strategy so weak, with an implementation base so broad, that we do little to actually improve the outlook of the STEM pipeline. As discussed below, a much more effective and vastly cheaper strategy is to match high-quality STEM educators with a relatively modest number of students who are most likely to be interested in STEM. If this is the strategy pursued, there is clearly no shortage of highly qualified STEM educators in the nation.

Increasing Teacher Pay Does Not Increase STEM Teacher Quality

Many advocates of the idea that broad-based improvement in STEM teacher quality is the key to addressing the STEM worker shortage argue that the best way to improve teacher quality is to attract more talented individuals to the teaching profession. Talent, not necessarily formal credentials, equates to improved student learning outcomes. Thus, in addition to boosting credentials of teachers, the goal is to hire better teachers however defined. In order to do so, the science policy community has generally supported increasing the salaries of STEM teachers, thereby lowering the opportunity cost of a high-quality individual pursuing a teaching career relative to more lucrative options.

In the 2010 *Science and Engineering Indicators* report, the National Science Board cited a study comparing the wages of public school teachers to workers of comparable skills and education. The report emphasizes study findings on the financial disincentives of choosing a career in education:

> Their analyses showed that in 2006, full-time public school teachers earned 86 percent as much in weekly wages as did those in this set of comparable occupations … A similar conclusion has been drawn about mathematics and science teachers—that is, their pay fell behind that of many professions with comparable educational backgrounds, and the gap widened substantially in recent years.[229]

Given that industrial positions pay more generously than do teaching positions (although this gap may be smaller when public-sector pensions for teachers are factored in), science policy organizations often recommend raising the salaries of STEM teachers to occupationally competitive levels.[230] Such salary increases are naturally assumed to lead to increases in student achievement in STEM. *The Education for Innovation Initiative*, a coalition of fifteen of America's most prominent business organizations (including the U.S. Chamber of Commerce), issued a recommendation that math and science teachers be placed on higher pay scales differentiating them from their non-STEM counterparts, asserting that it will "foster higher student achievement."[231] The report goes on to encourage school districts and governments to offer indirect financial incentives, such as low-cost teaching certifications, college loan forgiveness, low-interest housing loans, and stipends for new classroom technology and equipment.[232] All this, in turn, would theoretically attract more talented students into the STEM education field.

The attractive simplicity of raising teacher pay belies a complex downside. A systems-modeling study by the Raytheon Company suggests that pay raises cannot serve as a solution for improving the quality of STEM teachers, both in the short-and long-term. The model uses the U.S. education system as the basis for a "stock and flow model," with the students serving as the "stock." Modeled levels of interest determine the flow of students from one segment of the model to another, representing the dynamics of the STEM pipeline. In the short term, the authors highlight that school administrators lack the metrics to differentiate between more- and less-effective teacher candidates. (This is the same argument presented earlier, that a teacher's "paper" credentials have little predictive value with respect to students' performance level). As shown by their model, the resulting blindness in hiring largely negates the benefit of having a pay-induced larger candidate pool. As stated in the description of the Raytheon "system" model of STEM education:

> However, data show that increasing teacher pay does not result in better teachers. The model showed that an increase in teacher pay increases the candidate pool. This would improve teacher quality if school administrators hired the more capable new teachers from the larger pool of candidates, but there is an absence of data to support a conclusion that this will happen.[233]

In the long term, the authors suggest that industry salaries (which are more dynamic than those of the government, including our public education system) will simply rise in response, thereby negating the incentive built into the original salary increase:

> Increasing teacher pay shifts capable people from industry to education. When this shift of capable personnel from industry to teaching was modeled and industry was made endogenous, the model showed that such a shift resulted in a pay increase for industry candidates, which offset the teacher pay increase. The dynamic model showed the effect of teacher pay being slow to change and very inflexible, compared to industry salaries that are quick to adapt when shortages of necessary personnel occur.[234]

Educational researchers who study the relationship between teacher quality and compensation have reported similar findings.[235] One such report, based on the movement of teachers within the Texas Public School System, concludes:

> With few exceptions, advocates of across-the-board salary increases pay too little heed to teachers' classroom performance and to administrators' personnel decisions. A better policy approach is to focus much more on student performance and administrator accountability, while increasing the supply of potential teachers.[236]

It should be noted that other factors are far more effective in attracting pedagogical talent than salary. Generally, STEM studies have assumed that teachers value pay over other workplace qualities. However, polls demonstrate that other factors override the lure of higher salaries. As a recent report by the Center for Teaching Quality highlights:

> Another recent poll by the Public Agenda Foundation found that nearly 80 percent of teachers would choose to teach in a school where administrators supported them, rather than a school with significantly higher salaries. Recent research on National Board Certified Teachers (NBCTs) has produced similar findings. Our own work with NBCTs suggests that financial incentives alone will not lure these accomplished teachers to high-needs schools. Factors such as strong principal leadership, a collegial staff with a shared teaching philosophy and pedagogical practices, the autonomy to adapt curriculum to the needs of their diverse students (i.e., no rigid scripted curriculum), and access to subject-specific resources (e.g., classroom reading libraries and science equipment) are first and foremost. Financial incentives were important but not at the top of these teachers' lists. In one study we found senior teachers more than willing to transfer to high-needs schools if the conditions were ripe. Other researchers have also clearly documented what

> it takes to encourage accomplished teachers to move to the schools that need them most.[237]

The conclusion that teacher pay is not the driving force behind attracting pedagogical talent is supported by the fact that private schools pay only $39,690 per year to their teachers, compared to public schools' average of $52,230 per year.[238] In spite of the $12,500 salary differential, private schools still attract very highly qualified teachers, in part because many teachers see the work environment as more flexible and respectful of professional teachers. In short, other factors, such as strong administrative leadership, the opportunity to learn from experienced teachers in an open community, and creative control over lesson plans can supersede increases in pay and attract high quality teachers.[239]

As a whole, the body of work on teacher compensation suggests that across-the-board pay increases will do little to improve STEM teacher quality.

As a whole, the body of work on teacher compensation suggests that across-the-board pay increases will do little to improve STEM teacher quality. First, it is unlikely that pay alone will attract superior candidates to the talent pool, particularly in the public school system; other working conditions need to improve. Second, even if better candidates could be attracted, there is no way for administrators to discern which candidates are the "better" teachers within the candidate pool, since attributes that appear on paper have very low subsequent impact on student achievement (only 3 percent for teachers generally, as Goldhaber documented and only slightly more in the case of mathematics teachers).[240] Third, systems modeling of teacher pay have shown that, if STEM teacher salaries are raised, industry salaries for the same STEM-literate individuals will respond almost immediately, such that there will remain no net improvement in salary differential driving qualified individuals to teach, vs. working in an industry career.[241] And, finally, the salary differential would have to be very large—since the current $12K per year premium being offered isn't even enough to pull the best teachers out of private schools into public schools. Assuming an additional $10K salary premium would be needed per public school teacher (this also places teachers on pay level equal to their "comparable peer" base) and approximately 270,000 math and science public school teachers across the United States, we would have to spend about 2.7 billion dollars annually to achieve a questionable impact via this route.[242]

A National Curriculum and/or National Standards in STEM are Unlikely to Improve the STEM Talent Pool

As we have previously established, the STEM policy community has concentrated on expanding the talent pipeline by increasing the number of proficient K–12 students. It seems logical, then, to broaden participation in STEM by having all students learn the same STEM material and thereby reach the same standard of achievement. In this spirit, many STEM policy experts have argued that the United States needs to standardize its science curricula.[243] Science and math are, or at least should be, more or less universal across state borders.

Historically, the American education system has emphasized plurality and regional autonomy, as states retain the authority to design their own educational agenda.[244] As a result, there is a large degree of curricular diversity amongst school districts, as well as significant disparity between regional performance standards.[245] To counter this diversity, reports such as the *NSB's National Action Plan* outline the need for a coordinated curriculum, in both a "horizontal" and a "vertical" sense:

> Horizontally, STEM content standards and the sequence in which content is taught vary greatly among school systems, as do the expectations for and indicators of success. Because states have no consensus on what key concepts students should master and should be included in the curriculum at a certain grade level or within a specific content area, textbooks often cover too many topics at too superficial a level, rather than focus on a few key topics in-depth.
>
> Vertically, little or no alignment of STEM learning occurs during students' progression through school. Students do not always obtain mastery of key concepts at the elementary and middle school levels, thus limiting academic success at the high school level. In addition, many high schools provide a curriculum that is uninspiring, poorly aligned, outdated, lacking in rigor, and fraught with low expectations.[246]

The concept of curricular reform has been raised before in the sciences, albeit in a voluntary participation capacity. In 1996, the *National Academies released its National Science Education Standards* (NSES), which provided basic content guidelines for three separate segments of K–12 education.[247] Notably, the NSES also contained guidelines for high-quality instruction, with an emphasis on conceptual understanding over the rote memorization of facts. Similarly, the AAAS initiated *Benchmarks for Science Literacy* in 1993 to provide an outline of the essential components of scientific literacy.[248] Given the common authors between the two projects, it is estimated that their contents overlap by approximately 90 percent.[249]

Students at the School of Science and Engineering Magnet in Dallas, Texas work on an experiment.

The most dramatic step towards a standardized curriculum is the *Common Core State Standards Curriculum* (CCSS).[250] The CCSS Initiative is a joint education policy effort, led by the National Governor's Association and the Council of Chief State School Officers, which seeks to create a common core of K–12 content standards for the nation in mathematics and English language arts. A recent brief, *Update on the Common Core State Standards Initiative*, describes the project as follows:

> The state-led common core process is intended to produce "fewer, clearer, and higher" standards that are research- and evidence-based as well as internationally benchmarked. In preparing these standards, we drew examples from the most competitive states in the nation. The goal is to ensure that all students who meet these new standards will have the knowledge and skills necessary to succeed in college and a career, thereby improving the nation's competitiveness in today's global economy.[251]

The brief emphasizes concerns over global competitiveness (which mirror those of the STEM policy community on a broader scale) as a driving force behind the reform:

> Our economy is now truly global, and the competitiveness of our education system must reflect this. To maintain America's competitive edge, all of our students need to be well prepared and ready to compete not only with their American peers, but also with students from around the world. The state-led development of common core state standards is a critical first step to bring about real and meaningful transformation of state education systems to benefit all students.[252]

It should be noted that the English and mathematics standards have since been developed, and that their adoption by the states is purely voluntary.[253] The standards were released in June, 2010, following a yearlong assembly process by panel members representing 48 different states, 2 territories, and the District of Colombia.[254] Eventually, the program also intends to issue standards for science, in addition to its current standardization projects.[255]

In summary, many STEM policy experts (and educational policy experts) maintain that a new national curriculum should help teachers improve consistency, enhance clarity, prioritize concepts, deepen understanding, and facilitate the inter-regional transfer of students.

A key stated goal of STEM curriculum standardization is to improve America's economic competitiveness; however, competitiveness requires adaptability and flexibility, as well as rigor, and a national curriculum is not a tool that can deliver the former. By definition, curricular inflexibility means teachers cannot tailor their lessons to the needs and aptitudes of their students. As Robert Lerman and Arnold Packer of the Urban Institute note:

> All students should master a verifiable set of skills, but not necessarily the same skills. Part of the reason high schools fail so many kids is that educators can't get free of the notion that all students—regardless of their career aspirations—need the same basic preparation … Maintaining our one-size-fits-all approach will hurt many of the kids we are trying most to help."[256]

… there is growing evidence that suggests that what is needed is not a system of mass production with everyone learning the same thing, but rather a system of mass customization with learning tailored to differentiated interests. In other words, we need a system where students have more flexibility about what and how they learn.

Indeed, there is growing evidence that suggests that what is needed is not a system of mass production with everyone learning the same thing, but rather a system of mass customization with learning tailored to differentiated interests. In other words, we need a system where students have more flexibility about what and how they learn. Rigid standards can make this quite difficult to implement. Education reform experts Ted Kolderie and Tim McDonald describe this standards-based model as batch processing, where batches of students are all provided to the same education:

> When applied to education, batch-processing has obvious limitations. It requires all students in the class to proceed through the full term and at the same pace, affording little opportunity for those who need more time to take more time and little opportunity for those who could move faster to move faster. In the typical mixed-ability classroom, this confronts the teacher with a difficult, almost impossible, task. Moreover, educational course and content requirements too often tie the hands of students who want to pursue different or more sophisticated curricula.[257]

Linda Darling-Hammond also argues against a national curriculum due to its pedagogical rigidity, which impedes the development of programs that foster multidisciplinary viewpoints:

> As just one example, the new national standards are being written within traditional disciplines and even sub disciplines, which perpetuates older conceptions of how knowledge should be segmented and compartmentalized. They do not reflect the interdisciplinary perspective on teaching and learning that many state and local reforms are built on … Some states are developing curriculum frameworks in a more integrated fashion, including, for example, New York State's curriculum frameworks in "mathematics, science, and technology" and in "arts and humanities." With national standards determining the certification of local standards, would these be "uncertifiable" because they construe knowledge in a more interdisciplinary fashion than the federally sponsored projects?[258]

There are two key problems with the core movement when it comes to STEM education. The first is that if a course is not part of the core requirements it is essentially relegated to irrelevance (e.g., it is an elective). In this environment, and given the academic demands on college-bound students, they often have little room in their schedules for elective credits. And when it comes to allocating scarce resources, a school administrator will always focus on the "core" courses over electives. Being part of the "core" curriculum often makes the difference between courses (and teachers) that are given resources and those that are not. Computer science largely falls into this trap as only ten states now allow computer science courses, if they even exist, to count as a core mathematics or science requirement.

But the deeper and more troubling aspect of the core movement is that it assumes that high school students are all the same, that they have no unique interests and that for their own good they must be forced to all learn the same thing. But not all students are the same. Some have passions for English and writing. Others may love mechanics and engineering. Still others may be budding lawyers and be interested in American history and rhetoric. But for the school system, what the student is interested in is simply irrelevant. It's only when students get to college that they have some greater freedom, and even in many colleges and universities this is somewhat limited. As Kolderie and McDonald write:

> Conventional school is like a school bus rolling along the highway, with the teacher standing at the front and pointing out interesting and important sights but telling the passengers that, no, we cannot let you get off to explore what's down that side road. As a result students who want to pursue their interests and passions must do so on their own time and energies, if after completing all the required homework, they have any left.[259]

… the deeper and more troubling aspect of the core movement is that it assumes that high school students are all the same, that they have no unique interests and that for their own good they must be forced to all learn the same thing.

This goes a long way toward explaining why most American high school students appear to be bored with school. In the 2009 High School Survey of Student Engagement administrated by Indiana University, two out of three respondents (66 percent) are bored every day in class in high school; nearly half of the students (49 percent) are bored every day and approximately one out of every six students (17 percent) are bored in every class. Of those students who claimed they were ever bored (98 percent), the material being taught was an issue: more than four out of five (81 percent) noted a reason for their boredom as "Material wasn't interesting," and about two out of five students (42 percent) claimed that the lack of relevance of the material caused their boredom. The level of difficulty of the work was a source of boredom for a number of students: about one third of the students (33 percent) were bored because the "work wasn't challenging enough."[260]

In short, educational course and content requirements too often tie the hands of students who want to pursue different or more sophisticated curricula. Four years of English is not inherently superior to two years of English and two years of philosophy or two years of journalism, but in almost no American high school today does the student have that choice. The traditional American high school does not easily permit students who develop a particular interest to pursue that interest, no matter how strong the motivation or how useful the learning that might result. Alternatives sometimes exist for special-needs students and for those "not doing well," but the batch production model of education makes addressing the needs of these students expensive and still not very customized. For mainstream students and more talented students, there is not much in the way of alternatives. Is it any wonder then that so many young people drop out, with many of the students who stay doing so only because they see the link between putting up with a relatively unengaging process now for rewards later in life stemming from a high school diploma? Yet we carry forward almost unquestioned a batch processing model of school and teaching not designed to motivate either students or teachers. Instead of innovating to find new approaches, we try to improve performance by pushing ever harder to standardize and test.

… students who want to pursue their interests and passions must do so on their own time and energies, if after completing all the required homework, they have any left.

Prior Attempts at Standardization Have Not Yielded Significant Improvements in Learning Outcomes

In 2003, The National Academies reviewed the impact of the National Science Education Standards (NSES), promulgated as a set of voluntary curriculum standards beginning in 1996.[261] Their report evaluated the impact of these guidelines, finding some modest improvements in test scores, but little progress made towards reducing the achievement gap of minorities:

> The evidence that is available generally shows that investment in standards-based practices or the presence of teaching practices has a modest positive impact on student learning, but little or no effect on the "achievement gap" between European American and Hispanic or African American students.[262]

In defense of the lukewarm results from the National Academies' national curriculum experiment, it should be noted that the curriculum was both voluntary and unfunded. Thus implementation may have been the culprit rather than the standards themselves. This point was raised in the review:

> Overall, the evidence clearly supports the claim that states are moving toward the science education envisioned in the NSES … However, states have not progressed as far with translating standards into science curriculum … The summary study … found that curriculum had the lowest rating of change when compared to reform and policy initiatives. Therefore, the evidence indicates that while change is taking place at the state level, state policies overall are slow to influence change in the curriculum.[263]

What happens if curricular change is tightly tied to funding, and adoption is more or less mandatory? Here the impact evidence comes from the federal "No Child Left Behind" (NCLB) initiative. While not a planned curriculum per se, it is a de facto curriculum that is imposed by the existence of high-stakes standardized exams. "No Child Left Behind" has been in effect since January of 2002. Consequently, it is possible to roughly gauge the effectiveness of standards-based reform by comparing changes in math and reading proficiency prior to and after its enactment. It should be noted, however, that the effects of NCLB would not appear until after at least one full year of the program's passing into law. Since the first full school year under its influence was 2002–2003, we would not expect to see any effects of NCLB until 2003 at the earliest (more likely later).

The 2009 *National Assessment of Educational Progress* (NAEP), better known as "The Nation's Report Card," offers data on reading and math for the age groups 9, 13, and 17.[264] The last two intervals assessed are 2004–2008, and 1999–2004. As a simplifying rule-of-thumb, we will assume that the effects of NCLB were minimal prior to 2004, and more strongly felt thereafter. In mathematics, 9-, 13-, and 17-year-olds showed improvements in score of four, two, and one, respectively, over the period of 2004 to 2008 (with NCLB). In the preceding period (1999-2004), the respective score changes were nine, five, and negative one.[265] The score changes for the 17-year-olds (one and negative one) are considered insignificant. In reading, 9-, 13-, and 17-year olds showed score changes of four, three, and three, respectively, over the period of 2004 to 2008 (with NCLB). In the preceding period (1999–2004), the respective score changes were seven, zero, and negative three.[266]

Interpreting these results is not straightforward, but a few lessons can be gleaned. In mathematics, the scores are indeed improving, but actually at a slower rate than in the era prior to NCLB. For reading, NCLB shows considerable progress over most of the preceding period; the exception is with 9-year olds, who saw a larger improvement in the preceding period. Education expert Diane Ravitch, and a one-time supporter of NCLB, weighed in on the data in a recent commentary in *Education News*:

> In long-term trends, the achievement gap between white and minority students has hardly budged over the past decade. Although average scores are up for 9-year-olds and 13-year-olds in reading and mathematics between 2004 and 2008, the rate of improvement is actually smaller than it was in the previous period measured, from 1999 to 2004. It is time to ask whether NCLB should be renewed. I argue that it should not.[267]

Some other recent studies have found more encouraging results, though the data remain largely mixed. For example, one study found substantial improvements in fourth-grade math, modest improvements in eighth-grade math, but no effect on reading:

> We find that NCLB generated large and statistically significant increases in the math achievement of fourth-graders … and that these gains were concentrated among white and Hispanic students, among students who were eligible for subsidized lunch, and among students at all levels of performance. We find more moderate positive effects in eighth-grade math achievement. These effects are concentrated at lower achievement levels and among students who were eligible for subsidized lunch. In contrast, our results suggest that NCLB had no impact on reading achievement among either fourth- or eighth-graders.[268]

At best, NCLB seems to help some age-levels in some subjects; at worst, it has no benefit at all overall. However, if we are interested in enabling a small group of American students to excel in STEM, then NCLB and further standards efforts actually could be detrimental if they deter creating a curriculum that motivates students and enables them to become "Deep Divers," e.g., students who follow their passions to go deeply into particular areas of STEM (see Chapter 6).

Finally, we again raise the point of cost-to-benefit ratio. NCLB was not just about standards, it was about large expenditures to help raise standards. As Ravitch noted: "Results from this multibillion-dollar undertaking have been disappointing. Gains in achievement have been meager, as we have seen not only on NAEP's long-term-trend report, but also on the NAEP tests that are administered every other year."[269]

Overall, the data suggest that standards-based reform is neither a reliable nor cost-effective approach to correcting educational inequalities, nor does it succeed in promoting needed STEM education excellence. It may be that we simply do not know how to "do standards right," but for the moment, content-based standards do not appear to be a panacea for STEM achievement in K–12.

"BUILD IT AND WE HOPE YOU WILL COME": THE LIMITATIONS OF CURRENT APPROACHES TO IMPROVE STEM EDUCATION AT THE UNDERGRADUATE AND GRADUATE LEVEL

The three approaches described in this chapter—improving the public's (children's) interest in science, improving teacher quality, instituting national standards—are three of the more prominent "Some STEM for All" approaches. Yet, these are all K–12 approaches. There are several reasons why higher education has seen less of the "Some STEM for All" approach imposed upon it:

- Higher education is often seen as the terminal section of the "leaky pipeline," so efforts to expand inputs generally precede it.

- The structure of college enforces specialization (choosing a major), with the result that "Some STEM for All" is not entirely practical.

- While the Elementary and Secondary Education Act (ESEA) provides a means to implement "Some STEM for All" solutions across all K–12 schools, there is not a similar legislative lever to force compliance among all colleges and universities. Thus, colleges and universities have tended to be more independent and varied in their approaches.

The net result of all these factors is that, while higher education still faces significant challenges in producing a more robust STEM workforce, "Some STEM for All" solutions have not become entrenched in policy circles as "the answer" for higher education.

Instead, STEM policy on higher education usually focus on two areas: 1) providing more money to students to incentivize them to major in STEM, and 2) identifying promising practices in higher STEM education and publicizing these in the hope that individual colleges and universities—and STEM departments within them—will implement these changes. The latter can be referred as the "Build It and We Hope they Will Come" approach. The only problem is that while new solutions have been built, only a few colleges and universities have come to them.

There some evidence that financial incentives can help, but just as increasing K–12 teacher salaries is an expensive way to get more high-school grads to major in STEM in college, paying students to do so is also very expensive, especially compared with other equally or even more effective approaches. Thus, in later chapters we address institutional solutions that work for higher education, and pair these with institutional incentives for adoption. Some of the existing challenges that have been successfully addressed on a small-scale basis include the high dropout/switch out rate from STEM B.S. programs (Chapter 9), and a mismatch of graduates' skills with employer needs (Chapters 10 and 11). But to date, the scale of implementation has not been adequate to the scale of the need.

The fundamental problem is this: America's interest in getting more and better STEM graduates does not fully align with the interests of colleges and universities. Only by realigning these interests will we get better STEM education performance from colleges and universities. This can be done by, on the one hand, establishing a set of carrots and/or sticks to encourage other colleges and universities to follow suit, and on the other hand, by encouraging the creation of whole new colleges devoted to the kind of STEM education that is needed. We explore the problems, the solutions, and the needed drivers for reform in higher education under specific issue categories in Chapters 7–11.

> **America's interest in getting more and better STEM graduates does not fully align with the interests of colleges and universities. Only by realigning these interests will we get better STEM education performance from colleges and universities.**

CONCLUSION

In summary, policymakers should reserve some level of skepticism towards "solutions" to STEM manpower problems that rely exclusively on growing a pool of candidates at some prior stage in the pipeline. Such steps are rarely sufficient, and often expensive relative to their benefit. Improving public interest, providing teacher training in STEM subjects, and implementing national standards/curriculum in STEM have each had little effect for various reasons. And because they occur so early in the pipeline, subsequent gates negate any positive effects. The need to implement these solutions across all students in the nation, when only a few go on to STEM careers, also makes the "Some STEM for All" solutions prohibitively expensive relative to the benefit. While "Some STEM for All" is a worthy goal, "All STEM for Some" is a far more achievable goal, and the one immediately necessary for the creation of our next generation of technology innovators.

CHAPTER 5:

Teaching STEM Skills, Not STEM Facts

Students at School of Science and Engineering Magnet in Dallas, Texas.

Before discussing how to improve STEM education in K–12 education, it's important to first examine the broader question of what students need to learn in general. Current efforts to reform education generally, and STEM education specifically, are largely targeted at increasing subject matter learning. This significantly limits the ability to both design more innovative learning environments and enable students who are interested in STEM to pursue those interests much more deeply. In Chapter 6 we argue for redesigning the high school experience to enable students to go much more in depth into STEM. Here we discuss why the current focus on learning "what" as opposed to "how" limits student motivation, learning and choice. We also discuss how new forms of learning, including project-based learning and video-game-based learning can significantly boost student STEM learning.

In short, to improve STEM education, we need first to improve the learning environment. It is important to note that these challenges are not unique to the United States. One study that looked at STEM education challenges in a variety of nations reported:

> The quality of secondary and tertiary (possibly also primary) STEM education is mentioned in all countries as an important negative factor that does not contribute to young people's interest in STEM courses and professions. This education is generally seen as inaccessible, not relating to young people's everyday world and not paying enough attention to the relevance for society and the future. In secondary education subjects are insufficiently linked and teaching methods are mainly traditional: conservative teaching methods, a competitive atmosphere, and few active work forms and hands-on experiences for students. STEM courses in higher education are reported as too theoretical, insufficiently professionally oriented and not connected with secondary STEM education. Part of the instruction is given in large-scale formal lectures, by lecturers who are often more focused on research than teaching.[270]

WHAT K–12 STUDENTS REALLY NEED ISN'T KNOWLEDGE, IT'S SKILLS

The public school system arose in the Middle Ages, when books were rare and the knowledge in them prized. The Old English term, boeccraft, literally, "book creation," embodies this thinking and was used to connote literature, scholarship, and learning. The concept that factual knowledge and book learning are the desired end-points of education has permeated U.S. schooling to this day. The more "books" (subjects, courses) we absorb, the more learned we are supposed to be. Adolescents study disciplines abstracted from life: English, history, civics, physics, and mathematics. These are divided into courses, most of which are required for all students, and taught in formal classes. It amounts to production work with students processed by the batch; teachers instruct 25 to 30 or more students who move week-by-week through the subject and chapter-by-chapter through the text. The idea is to cover and to master the particular subject matter of the course rather than develop generic skills (e.g., the ability to analyze and to solve problems, to comprehend complex situations, to think critically, to be creative, to be adaptable, to be able to work with others and learn and re-learn over a lifetime). The assumption is that all students will know all subjects. Secondary students are tested mainly on their ability to recall factual knowledge. Success is defined as scoring well on tests for that knowledge, most involving testing for discrete, right-or-wrong answers.

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This focus on book-learned "knowledge" is evident in criteria used to guide textbook adoption, including long checklists of topics to be covered, rather than proof that the textbook under consideration has advanced the ability of students to do something.[271] Likewise, it's evident that high-stakes tests on long lists of facts or topics lead teachers to feel they cannot deviate from "teaching to the test." And, it is evident in high school graduation requirements in the form of an ever-expanding list of subjects rather than an ever-ascending list of abilities. Earlier this year, for example, the Texas Legislature added a fourth year of science and math to its already long list of subjects required for graduation.[272] The list of eligible fourth-year science courses, organized by topic, was 23 items long.[273] This medieval model of learning as an enlightened form of book memorization goes deep. In college engineering courses, small-group sessions devoted to hands-on problem solving with the help of an instructor, are still called "recitation"—as if engineering were a form of catechism class.

Long lists of content areas are not what students need to focus on to succeed. In the 2003 National Assessment of Educational Progress (NAEP) tests, 11 of the 15 lowest-scoring states in reading and math were textbook adoption states, e.g., those states that mandate the purchase of specific instructional materials for use in K–12 schools, based primarily on a long checklist of included topics (as well as avoidance of anything politically divisive).[274] By contrast, 13 of the top 15 states in math (including the top 5), and the top 11 states in reading were all states where schools are free to choose their own textbooks.[275] We are just barely entering an era where whether students learned anything, as opposed to whether they just sat in classrooms, is considered worthy of measurement and accountability. In line with this thinking, the federal government instituted "No Child Left Behind", and 26 states (as of 2007) began to ask for high school exit exams.[276] Now it is time to question what we should be learning, and therefore what we should be teaching, and testing.

Now it is time to question what we should be learning, and therefore what we should be teaching, and testing.

Students Need Skills

Knowledge, book-knowledge to be precise, is now all around us, thanks to the Internet. Push-of-a-button retrieval means rote memorization of facts is no longer necessary. Instead it will be skills—or the ability to use, manipulate, and apply that knowledge that will differentiate high-performing nations from the rest. This conclusion has been embraced, at least in theory, by popular culture, government, and the education establishment. A Google search on the phrase "21st Century skills" yields 281,000 results surrounding the concept of transitioning the school curriculum to a more skills-oriented approach. The Partnership for 21st Century Skills, an industry-education collaborative at the forefront of the skills movement, defines 21st Century skills as "critical thinking, problem solving, communication and collaboration," among others.[277]

Recently, a Conference Board-led survey of employers attempted to assess how well schools were delivering students with skills needed for the modern workforce. The results, a portion of which are shown in Table 5.1, were grim. In contrast to the 50 percent and stronger "very important" ratings for most of the skills in Table 5.1, the same employers rated "foreign language," "science" "government/economics," "history/geography," and "humanities/arts" as quite unimportant. The share of employers rating any of these as "very important" was 11 percent, 9 percent, 3.5 percent, 2.1 percent and 1.8 percent, respectively.[279] Thus, the subjects students are taught, in themselves, do not convey the skills employers need students to have.

Table 5.1: Employers' View of Skill Levels of High School Students[278]

Skill	% Employers Rating High School Graduates as "Deficient"	% Employers Ranking This Skill as "Very Important"
Written Communications (Business Writing)	80.9%	52.7%
Professionalism/Work Ethic	70.3%	80.3%
Writing in English (including grammar/spelling)	72.0%	49.4%
Critical Thinking/Problem Solving	69.6%t	57.5%
Mathematics	53.5%	30.4%
Reading Comprehension	38.4%	62.5%

Yet another view of the list of "essential skills" comes from standardized test publishers. As part of their work with employers to define workforce skills, the educational testing company ACT sent job profilers into companies to analyze exactly which skills were needed to perform specific jobs at each company. The result is a compilation of 16,000 different jobs profiled against a matrix of 9 skills. (Table 5.2) Each job, in effect, has a 9-digit "signature" describing the specific skills needed to perform it, at competency levels ranging from 3 to 7 for each skill (if the job needs a skill at only level 1 or 2, it is assumed that the job does not really require that skill).

Table 5.2: ACT-Defined "Fundamental Skills"[280]

Reading for Information	Teamwork	(Business) Writing
Locating Information	Observation	Workplace Observation
Applied Mathematics	Listening	Applied Technology

The skills in the first column of Table 5.2 are the most fundamental of the "fundamental skills." They reflect an individual's ability to take new information from a source, in whatever form it is presented ("reading for information"=text; "locating information"=diagram, chart, or other visual; applied mathematics=equation), digest it to the point of understanding it, and then turn around and apply that information in a practical, job-related situation. In other words, these three skills are the "learning how to learn" skills. And they turn out to be absolutely essential to almost all jobs. These skills appeared in the profiles of 80–90 percent of the 16,000 jobs analyzed.[281] This is not surprising, since only students who have "learned how to learn" can come up to speed quickly on any new task, regardless of whether they have previously received formal instruction in it. Because the "learning how to learn" skills are an essential part of what is needed to work, and because assessment instruments already exist for them, a number of states are now recommending or requiring students take the fundamental 3 ACT Workkeys tests as part of a statewide Career Readiness Certificate.

What is interesting about a skills framework is that the skills being suggested are universal across all subjects. Taking any of the lists as a starting point, we see we no longer need to teach classes or monitor progress against specific bins of information (history, English, math, science). Instead, we can target assessments to measure progress up a set of skill ladders, where the skills can be taught in the context of any subject the student (or teacher) finds interesting.

Suddenly it becomes possible to teach mathematical modeling of demographic shifts in social studies class, or to read literary histories of pivotal discoveries in science class. And the teacher receives credit for this innovative, integrative approach because assessments will show visible skill improvements in "reading for information" or "applied mathematics" regardless of the subject (knowledge) area in which the skill was taught. Now, teacher (and student) creativity has a much larger canvas on which to paint.
With a focus on fundamental skills, the richness of high school course offerings can be vastly increased, and their variety expanded—at the same time, students are made more "workforce ready."

As such, we no longer need educational standards based on the accumulation of factual knowledge. The key to building a skills-based education system to replace this, is skills-based assessment. Arguably, existing assessments (e.g., ACT's Workkeys) can be used to track whether students are moving up the skills ladder in the "learn how to learn" skills, but other tests will be needed to cover other skills. Indeed, the lack of national skills-based assessments, and/or the will to implement them, is the key impasse blocking education reform movements promoted by the various "21st Century skills" coalitions. Reports alone do not change behavior, high-stakes tests do. If we can test for what it is we really want to achieve, we might be able to move our education system towards the desired outcome of skills-based learning.

The conversion from subject-matter tests to skills-based tests as the focus of our nation's educational accountability is the key step missing in education's transition from an industrial era, facts-based mass production model to a 21st century, skills-based, mass customization model. In the former, students are viewed as empty knowledge containers to be filled with exactly the same knowledge in the same quantities; in the latter, they are viewed as individuals constantly applying and expanding key skills in the context of personal selections from a much broader cornucopia of subject matter domains.

Certain Additional Skills are Fundamental for Those Who Will Work in STEM

While generic skills are important, providing a robust education to STEM students will require more. But this does not mean more rote learning or factual repetition. Rather, the STEM portion of the high school experience should also be skills-centric, not knowledge centric. High school students could choose to engage with STEM or not, but if they proceed down a path of STEM electives, they would obtain the additional skills relevant to being a STEM practitioner. Those skills could be delivered in the context of any STEM content area the individual found personally appealing. Courses could even be reorganized such that they are labeled by skill area, with a single class devoted to developing a particular skill across physics, biology, chemistry, astronomy, or any science area.

Students at High Tech High in San Diego, California work together on a science project.

What are the STEM-specific foundational skills? The National Academies report, National Science Education Standards, strongly recommends that science education focus on the development of inquiry skills.[282] It briefly alludes to the fact that engineering has a primary skill set as well, namely design. No skill set is assigned to mathematics in this report, so we will loosely call mathematical skill "understanding and applying symbolic language." This accurately reflects the "learn how to learn" skill termed "applied mathematics" but broadens and deepens the definition to now include any symbolic language, thinking, and representation. Large portions of computer science would now fall under this definition. Arguably, some musical notations would also, since music is a formalized symbolic language for representing tonal frequencies and durations. The strong relationship between music and mathematics has been noted throughout history.[283]

With science, engineering and math defined in terms of core skills, we arrive at the three key skill sets that need to be conveyed to our STEM students:

Table 5.3: Fundamental skills that should form the basis of a high school curriculum in STEM

Old Subject	New Core Skill to be Taught
Science	Inquiry
Engineering & Technology	Design
Mathematics	Understanding Applying Symbolic Language

This list is important in that it not only gives a common focus for all of our course offerings, it also suggests metrics by which to assess the progress of our STEM students through high school. Each of the above skills can be subdivided into component "sub skills;" these sub skills are sufficiently well defined as to be testable. For example, *The National Science Education Standards* breaks down Inquiry into the following skills:

- Making observations
- Posing questions
- Examining books and other sources of information to see what is already known
- Planning investigations
- Reviewing what is already known in light of experimental evidence
- Using tools to gather, analyze, and interpret data
- Proposing answers, explanations, and predictions
- Communicating the results

Tests to see whether people can make observations already exist—note the "observation" test listed under the nine tests offered ACT/Workkeys. Similarly, the Educational Testing Service (ETS) developed a prototype test that addresses the third bullet in the above list, extracting information from written resources.[284] The ETS exam accomplishes this by tracking people's use of search terms and hyperlinks as they try to find information necessary to solve a problem. From the relevance of the search terms and the sequence of hyperlinks used, it is possible to determine, for example, if the individual is randomly searching, just hoping something useful will show up, or engaged in purposeful hypothesis-driven search and therefore likely to arrive at a relevant answer far more quickly. The latter approach generates a higher test score for "extracting information from written resources."

While the *National Academy of Sciences* (NAS), which authored the National Science Education Standards, strongly recommended inquiry be the focal point of science instruction, the NAS fell short of the mark by not giving any means by which to measure student progress in developing inquiry skills. And, since what is measured is what is delivered, it is no surprise that we have failed as a society to deliver inquiry-based science education. We recommend, therefore that the NAS work with a testing organization such as ACT or ETS to develop an explicit test for a student's progress in developing inquiry skills, using the above list of steps as a starting point for conceptualizing the test content. To ensure widespread adoption, federal and state funding for STEM curricula and STEM schools should be tied to the recipient institution's public posting of aggregate student scores on these tests, once they are developed. Restructuring college admission criteria around the "STEM skills" test scores would also motivate the adoption of these tests by high schools.

Without belaboring the point, it will be necessary for other organizations to take similar steps with their professions. If the National Academy of Engineering wishes to see the development of design skills become an integral part of high school STEM course offerings, it will need to work with testing company partners to develop an assessment of design skills. Project Lead the Way, which already places design-heavy engineering curricula in high schools, would be an excellent partner for the beta testing of this assessment tool.

For mathematics, appropriate tests may already exist—for example, the WorkKeys test alluded to above and the PISA test in mathematics for twelfth-graders. However, it would be worthwhile for mathematics and computer science organizations to form a panel to review these tests and determine to what extent they accurately address the "skills" that applied mathematicians and computer scientists need to have, as the majority of STEM jobs lie in these disciplines.

If the above suite of tests can be developed—tests to assess student progress in inquiry, design, and the use of symbolic language—then it should be possible to monitor student progress through all STEM courses (regardless of subject matter content) throughout the nation. High test scores can lead to the identification of high-performing schools, and with their permission, individuals as well. However, the most important use of these skills tests is for formative evaluation within a school. The science/math/engineering skills tests provide a means to characterize the skill set of an incoming class, adjust teaching methods and curricula accordingly, and monitor progress of cohorts along the way.

What About K–12 Content?

Skills are not practiced in a vacuum; they are applied in the context of content. While one can "test drive" one's skills through any content, knowing the content is like having a map: it makes navigation easier. Innovation—arriving at a new destination—contains fewer wrong turns if a map (content knowledge) is at hand. Thus, to facilitate STEM students' contributions to national innovation, we should provide them with accurate content knowledge. Skills are still paramount: you can't get anywhere with just a map, you need to be able to drive. But a driver with a map can go anywhere, directly and with purpose.

All too often, science is delivered as a series of facts. How many students have had to learn, "There are three types of rocks: igneous, sedimentary, and metamorphic?" The existing science standards purposefully move away from fact-based content, towards concepts.[285] If they are used at all, such standards represent an enormous improvement: we now have real maps instead of lists of streets. However, these lists of "STEM concepts every student should be taught" do draw their inspiration from historical legacy. "Life sciences" is included as a core concept because something called "biology" has always been in schools (at least, in our lifetime), not because it is more or less important than computer science, which is not included in such lists. To continue the map analogy, the state and national standards are lists of some of the available maps (concepts) in the STEM universe. Which maps a student really needs, depends on where he wants to drive. Drivers don't need a map of every state and town in the country, only the ones they are interested in visiting some day. And, if the travel plans change, the driver can get a new map (i.e., sign up for continuing education).

The STEM landscape is rich and varied. As a result, we argue that if students are taught navigation skills (inquiry, design, understanding and applying symbolic language) and then have the option of exploring what they are most interested in, through unrestricted course selection, they will eventually cover a reasonable segment of STEM landscape through these mechanisms. At the same time, the likelihood that more students will specialize in STEM increases because they will be able to focus on what they find interesting. One could even argue that students who wander into rarely charted territory have an even greater chance of making a singular/unconventional contribution later in life, compared to students who are exposed to exactly the same set of concepts as 15 million of their peers.[286] Consistent with this line of reasoning, we recommend against using state and national content standards to frame state accountability tests and textbook adoption standards, because the temptation is simply to ensure that biology concepts #1–29 are taught in ninth grade and physics concepts #30–60 are taught in tenth grade, etc. Whole swaths of the STEM landscape, outside these standards, then become inaccessible to STEM-impassioned students. And, the highly touted downside, that without universal STEM standards for everyone, the average student will not know the earth revolves around the sun actually has surprisingly few quotidian consequences.

Assess Conceptual Understanding with Concept Inventories

To continue the analogy, the current K–12 system ensures that each student graduates with a fixed set of maps (usually biology, chemistry, physics), but only of certain neighborhoods therein and gives no guarantees they know how to drive. We argue that the system should ensure that each student knows how to drive, gives them the maps they think they need or want, and ensures that those maps are reasonably accurate.

In terms of accountability, the state/nation would assure that each student has foundational skills via the statewide/national skills tests it imposes. Content (concepts), being individually selectable by the student and/or teacher, now no longer reside on state/nationally-mandated tests. It then becomes the teachers' responsibility to choose which concepts to help their students understand. It is also the teachers' responsibility to assure the concepts are "used" so as to require application of the foundational skills mentioned earlier. Because skills and concepts are two different things, it is important to be able to measure both. Measurement of conceptual understanding will need to reside with the teacher.

The way to assess, upgrade, and improve specific conceptual understanding is via concept inventories. These can be used by the teacher as both a formative diagnostic tool and a summative evaluation tool. Concept inventories assess conceptual understanding independently of facts and skills. For example, a "traditional" physics test might ask one to write down the equation describing the motion of a bomb that falls from a moving plane. This kind of problem conflates the skill of symbolic language manipulation and the knowledge of a memorized formula with the concept that x and y velocities are independent. Failure is possible on so many levels, it is hard to determine whether the student has not mastered the fact, the skill, or the concept. In contrast, the concept inventory will draw pictures of several possible trajectories for the falling bomb (all of which seem rather plausible) and ask the student to select the right one. Selecting the right one requires understanding that the x velocity is set by the moving plane, the y velocity is set by gravitational pull (and increases with time), and the resulting motion adds the two components, giving a new "arrow" pointing the direction of the falling object for each sequential point in time. No calculations are required and no formulas are needed.

Use of concept inventories allows the teacher to determine whether it is the concept or the skill that the student is missing. If it is the concept, then re-teaching the concept is necessary. If it is the skill (e.g., learning how to solve calculations), then re-teaching the skill is necessary. The archetype for all concept inventories is the physics concept inventory, originally developed by Halloun and Hestes.[287] However, in the past five years, NSF has funded the development of additional concept inventories for different fields. These include a biology concept inventory, developed at the University of Colorado and a computer science concept inventory developed at the University of Illinois. Libarkin recently reviewed the status of concept inventories in different fields.[288]

Use <g> Scores to Identify Teaching Methodologies that Maximize Conceptual Learning

Issuing a concept inventory test both before and after new concepts are taught allows each student's <g> score to be calculated, defined by:

<g> = (posttest percent-pretest percent)/(100 percent-pretest percent)

The <g> score normalizes for the fact that students enter a class with varying levels of pre-existing content understanding. Thus, the <g> score is a direct measure of the pedagogical effectiveness of an approach used to teach a concept, independent of the student's pre-existing state of knowledge with regard to that concept. If we use <g> scores as the ruler, we find different teaching methodologies yield vastly different learning outcomes, for exactly the same subject matter.

The first study to convincingly demonstrate this was conducted by Richard R. Hake in 1998, who examined the results from Physics Concept inventories given to 6,542 students, located in 62 physics classes across a wide variety of school types and instructors (the study included 14 high school, 16 college and 32 university courses). All students were supposed to have learned the concepts in "introductory physics" according to virtually identical syllabi. However, how those students were taught that material led to marked differences in <g> scores. Hake found <g> was 0.23 ±0.04 for courses taught in the conventional (classroom lecture) manner; <g> =0.23 is quite a low score, considering <g> varies only on a scale of 0 to 1 overall. Moreover, the lecture <g> was remarkably unchanging (a variation of only 0.04), despite the many different lecturers used. This finding, in particular, underscores the point that the method by which information is conveyed has its own limitations, and the quality of the teacher/professor can budge the dial only a bit.[289] (Recalling the earlier discussion on teacher quality in Chapter 4, we see now that the use of ineffective pedagogical approaches, such as lectures, is probably one of the "unmeasurables" that distinguish bad teachers from good, but do not appear anywhere on a resume and are not related to an advanced subject matter degree).

> **… changing the quality of the lecturer improved instruction by about 17 percent while switching to a different mode of instruction entirely, to something that required student interaction (often using the same teacher) improved instruction by 108 percent.**

In comparison to the <g> value for lecture classes, <g> was 0.48 ±0.14 for courses in which students had at least some kind of "interactive engagement." In other words, changing the quality of the lecturer improved instruction by about 0.04/0.23=17 percent (the variation between lecturers at different schools) while switching to a different mode of instruction entirely, to something that required student interaction (often using the same teacher) improved instruction by (0.48–0.23)/0.23=1.08 or 108 percent. Thus the way in which content is delivered is exceedingly important to students' grasp of it.

Build a National "STEM Test Kitchen"

Teaching approaches that maximize <g> scores should be widely promulgated and adopted for the instruction of STEM students. We recommend that NSF use concept inventories and <g> scores to unambiguously identify the most effective teaching methodologies for imparting specific, commonly-taught concepts in STEM fields (such as falling bodies in physics). More specifically, we recommend that NSF issue a contract with an organization to construct a showcase "STEM Test Kitchen," perhaps located adjacent to the NSF headquarters in Arlington, Virginia, to test different STEM teaching approaches, side-by-side, and determine which is best suited to delivering a specific concept. The laboratory would take in groups of students, apply a concept inventory pretest, teach a concept using a particular approach, then administer a concept inventory posttest. The same concept would be taught to different batches of students, using different teaching approaches. As seen in the Hake example, the concept inventory's <g>

score allows results to be normalized between and among different batches of students, and even across teachers, to arrive at a clear indication of the effectiveness of the methodology used.

The "STEM Test Kitchen" concept is not unlike "America's Test Kitchen" for testing different approaches to, say, parboiling a chicken, to see which delivers the best combination of flavor and texture when the chicken is ultimately baked. And, like "America's Test Kitchen," the results of these side-by-side comparison tests can be disseminated via a TV show or popular magazine for the STEM teaching community. Or, using a more modern approach, the "winning approach" could be distributed via YouTube video. In much the same way as a cooking show segment shows how to cook a specific item, this video would show how to teach a given concept, along with the corresponding concept inventory questions so that teachers who wish to try this on their own can see if they match NSF's standard for effective concept teaching.

In Chapter 4, we noted that teacher training that focused on imparting subject matter knowledge was a weak approach to improving teaching. Much of the effectiveness of a good teacher was wrapped into "unquantifiable" variables that related to how the teacher taught. With this recommendation for an America's STEM Test Kitchen, we can begin to unpack the mystery of how different teaching approaches produce different learning results.

EFFECTIVE (INTERACTIVE) TEACHING METHODOLOGIES

The Hake study showed that interactive teaching approaches far outshine the standard lecture.[290] However, that study lumped a number of different interactive approaches into one bucket, which probably explains why the standard deviation among those <g> scores was so high. Effective, interactive teaching models are not all one flavor. Hopefully, the "STEM Test Kitchen" will be able to sort out gradations of "goodness" to arrive at optimum teaching methodologies for specific concepts. Two promising interactive approaches are project-based learning and game-based learning.

Project Based-Learning

Can project-based learning provide opportunities for students to delve more deeply into STEM topics than is possible in typical high school STEM classes? Studies of project-based learning suggest a wealth of potential for deeper learning.[291] However, realizing that potential is not a simple undertaking.

The premise underlying project-based learning is that challenging real-world problems can sustain students' interest and stimulate critical thinking as they acquire and apply their knowledge. In stark contrast to traditional teacher-directed classes, students work in teams on problems that are complex and worthy of extended investigation. The role of the teacher shifts from transmitter of information to that of facilitator, helping students develop worthwhile questions, structure appropriate tasks, acquire new knowledge, and work collaboratively. If the project is rich and well-designed, students can delve far more deeply into a subject than traditional textbook-oriented instruction permits.

Students at the School of Science and Engineering Magnet in Dallas, Texas work together on a project.

Research suggests that this is indeed the case. The 2009 High School Survey of Student Engagement asked high school students to rate the degree to which various types of instructional methods excite and/or engage them.[292] Students rated most highly those methods that involve work and learning with their peers. "Discussion and Debate" was rated as "to some degree" or "very much" exciting/ engaging by about three out five students (61 percent), while only 16 percent of respondents rated this instructional method as "not at all" exciting/engaging. "Group Projects" were rated similarly: 60 percent of respondents rated this instructional method as "to some degree" or "very much" exciting/ engaging, while only 17 percent rated it as "not at all" exciting/engaging. "Projects and Lessons Involving Technology" was chosen by 55 percent of students as an instructional method that was exciting/engaging either to some degree or very much. Students reported being least excited/engaged about instructional methods in which they do not play an active role: "Teacher Lecture" was rated as "to some degree" or "very much" exciting/engaging by only 26 percent of respondents, while 44 percent of the respondents rated this instructional method as "not at all" exciting/engaging.

Unfortunately, project-based learning has never gained a strong foothold in schools, particularly in secondary schools where traditional teacher-directed instruction is the overwhelming method of choice among teachers. Typically, project-based learning occurs when an individual teacher chooses to take on one or more projects during the school year. At the other end of the continuum, a few schools use project-based learning as their primary method of instruction. These tend to be specialty schools such as Virginia's Thomas Jefferson High School for Science and Technology; High Tech High in San Diego, California; Minnesota New Country School in Henderson, Minnesota; NewTech High in Napa County, California; and Tech Valley High School in Rensselaer, New York.[293] Motivated students without either teachers or schools dedicated to problem-based learning can sometimes find opportunities outside the regular curriculum. In fact, in many high schools, the most common form of project-based learning exist in after-school computer groups, robotics clubs, and competitive math and science teams. Summer institutes focused on STEM learning provide additional opportunities.[294]

... in many high schools, the most common form of project-based learning exist in after-school computer groups, robotics clubs, and competitive math and science teams.

While many schools that employ project-based learning use it to supplement lectures, some schools have largely replaced lectures and even classes. A leading example of this approach to project—based learning is Minnesota's New Country School. New Country School is a teacher-run co-operative chartered school with a project-based pedagogy. Each student has a workstation, complete with desk and personal computer. Students work with advisors to achieve course content requirements. They can incorporate IT in any way they see helpful: email, podcasts, online specialty courses, personalized tutoring software, and document software that lets teachers jointly review work. New Country School describes itself the following way:

> The school is based upon the idea that students will be most engaged in the learning process when they have a personal interest in what they are learning. Instead of sitting in a teacher-driven classroom all day long, students learn through the exploration of topics that interest them on their own terms, and largely at their own pace. Each student is a member of a team of twelve to twenty students, managed by an adult advisor who helps to facilitate the learning process. Instead of grades, students receive credit for their work. The process is completely flexible, and can be tailored toward specific learning styles, prior student knowledge, student motivation, etc.[295]

Projects can serve many different purposes depending on the subject and students' level of knowledge and motivation. For example, students in a physics class might investigate vectors through tracking airplane flights. Or students might reverse engineer a camera and create a systems diagram and directions on how to reconstruct it.[296] The more advanced and self-motivated the students, the more complex the tasks can be and the more independent the work can be. At the high end, for example, two national prize-winning students worked together on streamlining the gene discovery process by combining traditional genetics with cutting-edge computational modeling.[297]

Although projects are the primary vehicle for learning in project-based learning, there are no commonly shared criteria for what constitutes an acceptable project. Projects vary greatly in the depth of the questions explored, the clarity of the learning goals, the content and structure of the activity, and guidance from the teacher. As a consequence it is difficult to identify a distinct body of research on project-based learning, and even harder to find studies that measure effects of project-based learning on student achievement.

In general, evidence suggests that project-based learning can increase student learning, both in general academic achievement and specifically on measures of conceptual and applied knowledge. A review of project-based learning research in 2000 cites about a dozen studies in which project-based learning is associated with increased ability to apply knowledge in new problem-solving contexts, and in many cases, with improved scores on standardized or classroom tests. While no negative effects are reported, the scale of many of the studies is small, not all have comparisons with other teaching methods, and the size of the observed positive effects varied greatly.[298]

Studies most relevant to high school students using project-based learning in STEM subjects are limited in the United States, but a few can be found in other nations. A study in Great Britain compared mathematics achievement in two similar secondary schools, one using traditional instruction and the other using project-based instruction. The two groups of students had similar scores on the national exam at the beginning of the study. After three years, significantly more students in the project-based-learning school passed the national exam (88 percent vs. 71 percent) and three times as many students attained the highest possible score. British students in the project-based-learning school outperformed the traditional-school students in mathematics skills as well as conceptual and applied knowledge based on an analysis of subsets of items on the standardized national

Two students at Carnegie Mellon University in Pittsburgh, Pennsylvania work together on an engineering project.

exam. In addition, six months later these students retained more (remembering one-half of measured knowledge compared to one-third for their traditional counterparts). What's more, the correlation between performance and student social-economic status declined in the project-based school (from .43 to .15) while increasing in the traditional school (from .19 to .30).[299]

Similarly, Israeli researchers studied high school high achievers tackling the design and implementation of solutions for technological problems through project-based learning. Students showed a significant increase in their formal knowledge as measured by changes in scores from pretest to posttest on the standardized Israeli matriculation exam based on the course syllabus. Scores for students learning through projects increased from 2 percent correct items on the pretest to 86 percent correct items on the posttest (a change of 84 percentage points) while those learning through traditional coursework increased from 23 percent to 75 percent (a change of 52 percentage points).[300] Students in the project-based classes also demonstrated expanded technological knowledge in carrying out their projects and in the resources they utilized, as well as more positive attitudes towards technology and technological studies.[301]

Most studies of the impact of project-based learning on students' achievement have investigated well-developed programs rather than projects created by individual teachers, which are much more common. Research on these more typical versions of project-based learning focuses on the challenges of implementing projects in classrooms rather than their impact.

Project-based learning faces multiple implementation challenges, some deriving from the structure of schools and others from the added demands on teachers. These include the length of class periods and the pressure on teachers to cover many curriculum topics. Inquiry-based projects take more time than teacher-centered instruction does; projects typically extend over several days or even weeks. Moreover, many teachers feel under the gun to cover topics likely to be on the state- or other high-stakes test as a result of the accountability requirements of No Child Left Behind (NCLB). With sanctions attached to failure to reach test-score targets prescribed by states under NCLB, districts and schools tailor their curriculum and time allocations to the subjects and particular topics that are tested, namely reading and math.[302] In this environment, project-based learning loses out to more conventional lecture approaches.

Great Britain students in the project-based-learning school outperformed the traditional-school students in mathematics skills as well as conceptual and applied knowledge based on an analysis of subsets of items on the standardized national exam. In addition, six months later these students retained more.

Moreover, projects increasingly rely on information technology (IT)—typically computers with Internet access—to provide simulations, opportunities for on-line research, or collaboration with others in remote locations. Reliance on IT requires both convenient access to the appropriate hardware, software and connectivity, as well as knowledge of relevant websites, both of which place additional demands on teachers.[303]

Inquiry-based teaching through projects is much more difficult than traditional teacher-centered instruction. Helping students create the right-size problem requires teachers who fully understand the concepts embedded in potential projects, and who can model thinking and problem-solving strategies effectively.[304] Worthwhile projects require challenging questions that are meaty enough to support serious investigation and collaboration, as well as methods of measuring the intended learning outcomes. Implementing projects also requires additional skills that are not in every teacher's repertoire, such as managing multiple activities and helping teams work collaboratively.[305]

Because of the extra demands on teachers, there is substantial difficulty in finding and keeping the effective school leaders and teachers required to implement project-based learning—similar to the recruiting problems encountered by charter schools nationally.[306] San Diego's High Tech High, for example, encountered severe difficulties when it tried to replicate its approach in partner schools across the country, in part because it could not find teachers and leaders like the ones at the home school. In the end, it decided on a replication strategy that focused on creating new schools close to the parent school (so the principal could be personally "on call") and on seeding those new schools with its own personnel. With this strategy High Tech High grew from its original location to five high schools in nearby communities over a 10-year period, with a $17M investment from the Gates Foundation.[307]

Effective project-based learning also asks more of students, many of whom are accustomed to passive forms of learning. Students need to be interested enough in the problem to put out sustained effort, and they need sufficient background knowledge and skills in techniques such as data collection and analysis. Students must also develop skills in working collaboratively and in organizing and managing an extended project.[308]

Project-based learning also costs money—not a lot, but enough to present a challenge in many school districts. Resourceful teachers (and even national competitions, such as National Lab Day) have turned to crowd-sourcing micro-donations to get student projects off the ground; an entire website (donorschoose.org) now solicits micro-donations for classroom improvements generally and school projects specifically.

Student at High Tech High in San Diego, California work closely with their teacher on a project.

These challenges underscore the difficulty of implementing project-based learning successfully. High school teachers often assign projects to students, but most are a far cry from the kinds of learning experiences embodied in high-quality project-based learning. Without school leaders who support projects, carefully designed tasks, and skilled teachers, project-based learning can devolve into a string of activities with no clear learning goals or measurable outcomes.

Yet when conditions for success can be met, the potential payoff is large. Students learn in-depth knowledge about the problem they are investigating, sharpen their inquiry skills, and can apply what they have learned in new situations. Project-based learning also offers a way to interest and motivate students who may have great promise but have tuned out.

As U.S. high schools and STEM courses are currently organized, project-based learning is likely to remain the exception. High schools that have succeeded in building teaching and learning around projects tend to be charter, magnet or STEM schools—schools of choice that attract strong school leaders as well as teachers and students interested in inquiry-based learning.

As U.S. high schools and STEM courses are currently organized, project-based learning is likely to remain the exception. High schools that have succeeded in building teaching and learning around projects tend to be charter, magnet or STEM schools—schools of choice that attract strong school leaders as well as teachers and students interested in inquiry-based learning. Such schools are not locked into the conventional organization and pedagogy that permeates most high schools. As such, it's easier for them to shift to more project-based learning.

However, project based learning could grow if more specialty STEM schools are created. It could also grow if it gradually became more of the norm for teaching. People would go into "teaching" knowing that they are not so much "teaching" as facilitating the learning of students through projects. Changing from testing of knowledge to testing of competencies, as described above, would also free up more teachers to feel confident to take the risk of moving to project-based learning.

Videogames-Based Learning

Videogames are widely enjoyed by incredibly large numbers of people, across all ethnic, racial, economic, and geographic divides.[309] The Entertainment Software Association's annual survey reports that 68 percent of American households play computer or video games; that figure rises to 82 percent for full-time students (combined male and female).[310] However, it is not just the sheer number of people that videogames reach that make them an attractive partner for STEM reform. It is also the pedagogical structure of the games themselves. At first glance, it may be surprising that videogames are effective learning tools. But when considering the findings from the Hake study, that interactive learning approaches are almost twice as effective as lecture, it should not be that surprising.[311] Consider that in the average videogame, feedback (interaction) is continuous and immediate, on the scale of seconds. By contrast, in a typical classroom, a student gets to ask 0.11 questions per hour.[312] By at least that one measure, videogames should be more effective than lecture.

A recent overview of videogame-based learning confirms their effectiveness as learning tools. The review examined learning outcomes for games, and for STEM games specifically.[313] The STEM games cited covered topics as diverse as numerical methods, ecology, biology, geography, and electrostatics, to name a few. The learning outcomes for these STEM video games ranged from 7 percent to 40 percent better than lecture.[314] The smallest differences were for situations where the control was a classroom taught by a highly interactive teacher (e.g., in the case of the electrostatics game Supercharged!); the largest differences were for cases where the control was a large college lecture class (e.g., Virtual Cell, which covers college cell biology).

The superior learning outcomes of videogames are in part due to frequency of interaction, but pressing a button alone obviously does not yield learning. It is the surprisingly rich pedagogical structure that games embody that explains why pushing a button translates to learning. The pedagogical features of educational video games include the following:

- Adaptable Learning Rate: The pace of learning is set by the user, at whatever rate preferred. Learner Control/Autonomy: The learner decides how to navigate through the material, thereby becoming more engaged in, and committed to, the learning activity. Learner control and autonomy have positive impacts on learning outcomes and motivation, respectively.[315]

- Social Context: Socially relevant problems and specially constructed social interactions drive learner engagement, as studied in depth by Barab, et al, in their *Quest Atlantis* project.[316]

- Multiple Representations: Information is presented via audio but also video, via words but also symbols, via the static environment but also via the actions/reactions of characters and game elements. These multiple representations assist in accommodating different learning styles.

- Just-in-Time/on-Demand Delivery: Information is presented when most needed by the learner, often at the explicit request of the learner.

- Situated Meaning: Information is presented within an overall context, often a narrative or environment, whose other elements reinforce that information. Almost never is information presented completely devoid of context.

- Incremental Staging of Information Delivery: Information is delivered in small, digestible doses. Complex tasks are similarly presented first as a small core experience that is practiced multiple times, before being progressively extended into a longer, more complex sequence. The efficiency of this approach (concurrent chaining) compared to whole task learning has been quantified.[317]

- Inquiry-based Learning: Rarely is the game player told the right answer; instead, one learns via formation of hypotheses, experimentation, and discovers the consequences of actions/experiments.

- Goals: Students persist longer in a task if working towards a goal. Games, almost by definition, have goals.

- Multiple Pathways: Most goals in games can be reached by multiple routes, and so the learner must make choices based on a comparison of predicted consequences. This structure requires the learner to operate at the highest level ("Evaluation") in Bloom's *Taxonomy of Educational Objectives*.[318]

- Self-Efficacy: The learner's own perception of how well s/he is doing translates to greater persistence and ultimately a higher level of accomplishment. Games foster self-efficacy by rewarding the player immediately for even the tiniest successes, through progressive accumulation of points and levels.

- Time on Task: More time on task, more material learned. The five to eight hours a week spent by teenagers playing games equal or surpass the time college-bound high school students spend on homework.[319]

- Collaboration: Collaborative learning yields, on average, a 50 percent improvement over solo learning.[320] Many of the massive multiplayer online games have collaborative problem-solving hardwired into their architecture (e.g., group quests).[321]

To summarize the above list, videogames are well structured to be learning experiences: they embody a high feedback frequency to the user, explicit goals, embedded reward systems, hierarchically tailored difficulty, multimodal engagement (simultaneous audio, visual, & kinesthetic inputs), user control over navigation (self-directed pace and content choice), on-demand help systems, collaborative learning/peer reinforcement (in multiplayer games), and more. We argue that videogames not only teach effectively, but develop such strong motivations in learners; they can almost singlehandedly transition a motivated "casual gamer" into a budding STEM professional, much as an effective teacher might.

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The path from game-initiated engagement to subsequent passion for STEM is best illustrated by the game NIU-Torcs designed to teach numerical methods via a racing car game.[322] Numerical Methods is a dry, mathematics-intensive course required of upper-level engineering students in college. However, at Northern Illinois University, those learning numerical methods via the custom-designed NIU-Torcs game were hooked: statistical analysis showed users to be 0.82 standard deviations more "engaged" (on a personal scale of "not-at-all" to "entirely" engaged) when working with NIU-Torcs as compared to a random sampling of other times during the day.[323] And, despite the fact that they spent twice as much time on the game-based homework as their colleagues in traditional textbook drill on regular homework, 90 percent voluntarily elected to go on to take the advanced numerical methods class.[324]

Foldit is another game that transforms gamers into STEM practitioners.[325] Downloaded more than 100,000 times in under a year, this game allows users to bend, twist, and manipulate proteins to try to get them into their optimum (minimal-energy) configuration. On one level, *Foldit* is an addictive 3D puzzle game, but at another level, it allows humans to experiment with and discover new protein structures that are as yet unknown to science. And, at the 2008 Community-Wide Experiment on the Critical Assessment of Techniques for Protein Structure Prediction, or CASP, it was a 13-year-old boy, playing Foldit, who not only uploaded seven winning solutions, but also walked away as the winner of the CASP protein-folding competition. Up until that time, winners had been research scientists working with high-powered computers.[320] Other games focus on engineering. For example, IBM designed *PowerUp*, a free multiplayer online game, to help attract students to careers in engineering. The game teaches students about science, math and engineering principles as they save the planet Helios from ecological disaster.[326]

Even entertainment games can create STEM practitioners. *The World of Warcraft* game, for example, spawned an Elitist Jerks Forum, where individuals obsessed with this fantasy game post mathematical models of character behavior, quantitative analyses of character-game interactions and object-character interactions, and data sets supporting or refuting claims of superior tactical or strategic approaches to an in-game goal.[327]

This informal cadre of statistical and mathematical experts self-assembled with respect to the theory craft of a particular game. However, their deep obsession evolved to an understanding of events at the mathematical level, and their need to arrive at rational decisions necessitated an ability to support their arguments with scientific logic. Those same skills, if we could quantify them outside of a degree-granting institution, would probably render these individuals eligible for a variety of STEM jobs requiring applied mathematics. Indeed, one could argue that the ability to visualize orc weapon-wielding behavior as a mathematical algorithm, and correctly model that algorithm, is more genuine evidence of applied mathematics skill than solving problems at the back of a textbook.

Games could complement textbooks in the classroom and lead to more highly engaged learning. At present, the adoption rate of these new media in schools is slow, largely because of distribution channel issues.[328] However, a key policy limitation is the way in which textbook adoption criteria are framed. Long lists of topics to be covered tend to favor the adoption of textbooks that no one reads; a revision of these criteria to prove that something (preferably skills) are actually learned, would tend to favor games and other interactive media. Without explicitly endorsing games over textbooks, this change would allow all media to be the best learning tools they can be.

Fostering Effective, Interactive STEM Learning in College

The Hake study showed that high levels of interactive engagement yield strong learning outcomes in STEM (or, at a minimum, physics). Quantitative evidence on the benefits of project- and game-based learning suggests the same. Unfortunately, while many K–12 instructors may miss the boat in terms of interactivity, college instructors are systematically much worse off (recall games were a small improvement over K–12 instruction, but a huge improvement over college instruction). In higher education, particularly in public colleges and universities, the overarching cost structure for STEM relies on low cost mass lecture classes in a student's early years to offset the otherwise prohibitive price point of small laboratory classes in later years. Non-interactivity, especially in the first two years of curriculum, is not just a random oversight. It is an institutionalized omission, enforced by financial considerations.

Different organizations have taken different approaches to solving this problem. Project Kaleidoscope, an organization exclusively devoted to reforming undergraduate STEM education, takes on the challenge of interactivity by developing future leaders who embrace interactive approaches, and also by promoting classroom space redesign, to facilitate non-lecture learning.[329] It also delivers the message in its "What Works" reports.[330] We believe what works is when the total environment is infused with opportunities for hands-on, collaborative, and investigative learning. Recently, Project Kaleidoscope has turned to undergraduate research as a mechanism for ensuring relevant interactive experiences are used in the undergraduate curriculum.[331]

Individual universities have also taken it upon themselves to forge ahead with greater interactivity in the STEM curriculum. Interactive learning is point 3.2 in *The Rensselaer Plan*, which nurtures and enhances interactive teaching and learning as an Institute wide enterprise. The plan calls for a new educational approach to:

- Investigate new interactive pedagogies across all curricula, forging a deeper relationship between student and teacher.

- Engage students in collaborative learning experiences, taking advantage of technology to facilitate interactivity and teamwork skills to solve problems.

- Customize the learning experience to individual needs, deploying interactive pedagogies to engage a full range of backgrounds and learning styles.

- Use interactive pedagogies to create "virtual environments" that extend the student experience in time and space, sharing courses among universities and creating virtual classrooms, discussion groups, and project settings with faculty and students at other universities, and with researchers, innovators, entrepreneurs, and policy-makers around the world.

- Develop continuous and interactive assessment techniques so that testing becomes a tool for learning.

- Pursue leadership in the use of technology in education, developing deeper understanding of how we learn, accelerating the pace of innovation in interactive learning, and providing opportunities to showcase innovative results.[332]

While individual efforts such as these are highly laudable, they are conducted in the face of systemic financial disincentives to deliver interactive learning at the college level. A clear counter-incentive, widely available across the entire U.S. higher education system, is in order. Offering higher reputational rankings in return for higher levels of interactive student engagement is one approach to systematically reward institutions where interactive teaching is the norm, and penalize those that rely on pedagogically poor mass lectures.

Fortunately, there already exists a measure of student interactive engagement—the National Survey of Student Engagement scores (NSSE). The National Survey of Student Engagement, begun with support from the Pew Charitable Trusts, is designed to obtain, on an annual basis, information from more than 1,300 colleges about student participation in programs and activities that those institutions offer for learning and personal development. The results provide an estimate of how undergraduates spend their time, what they gain from attending college, and their views about the quality of teaching that they've received. Even though the survey doesn't measure education outcomes, it measures the activities and practices that are associated with those outcomes. Indeed, it states, "Survey items on the National Survey of Student Engagement represent empirically confirmed 'good practice' in undergraduate education. That is, they reflect behaviors by students and institutions that are associated with desired outcomes of college."

The NSSE asks students how often they have had certain experiences on campus, such as "making a class presentation," "working with other students on projects during class," "using e-mail to communicate with an instructor," discussing ideas from your readings or classes with faculty members outside of class" and many more.[333] These responses are combined to rank universities on their "Level of Academic Challenge," "Active and Collaborative Learning," "Student-Faculty Interaction," "Enriching Educational Experiences," and "Supportive Campus Environment." The NSSE therefore measures not only the level of interactivity, but other aspects of the college experience that should be important to the discriminating parent and/or student. Unfortunately, universities who contribute to this survey are neither required nor incentivized to publish their survey outcomes. Olin College, featured in Chapter 7 is an exception (it also has very high NSSE scores). We suggest three remedies, so that students, parents and funding agencies can determine which institutions are dedicated to providing a compelling pedagogical experience—and so that these stakeholders' dollars, more wisely spent, can lead the way for change.

1. As a "check off" criterion in the certifications and representations section of any grant proposal that provides student support, universities should have to assert that they have publicly posted their National Survey of Student Engagement (NSSE) results. The release of this information will allow funding agencies, students, parents, and other stakeholders to ascertain that institution's level of student engagement in instructional practices designed to foster deep learning. The Office of Management and Budget (OMB) is in a position to enforce this measure across all STEM funding agencies, through its form approval processes.

2. Through the awarding of prizes, foundations could create a culture where universities strive to top each other in NSSE rankings. Philanthropic foundations committed to fostering excellence in STEM education could provide significant prize money for the top three to five NSSE-ranked departments.

3. In its annual ranking of U.S. Colleges and Universities, the *U.S. News and World Report* should start including NSEE scores and rewarding colleges and universities that report their scores with higher ranks.

Theoretically, there is no reason to limit the use of the NSSE to undergraduate education. Indeed, a similar instrument could be used to gauge the use of effective teaching practices in high schools. At least one such test (the High School Survey of Student Engagement) has already been developed.[334] Validation testing (psychometric testing and showing a correlation between test results with learning outcomes) would, however, be necessary prior to having scores tied to monetary rewards.

At the collegiate level, expanding project-based learning, undergraduate research, game-based learning, discussion-style classrooms and other interactive techniques parlays benefits well beyond giving undergraduates the best pedagogical experience available.

At the collegiate level, expanding project-based learning, undergraduate research, game-based learning, discussion-style classrooms and other interactive techniques parlays benefits well beyond giving undergraduates the best pedagogical experience available. It addresses the question of how to inculcate these practices in K–12 instruction as well. Immersing teachers during their own college years—when they themselves are being trained to teach—in the very instructional model we wish them to emulate in K–12, should make it natural for them to bring these techniques to the next generation. People teach, as they themselves were taught.

CHAPTER 6:

Creating STEM Deep Divers in High School

High Tech High in San Diego, California strives to integrate technical and academic education to prepare students for post-secondary education in both high tech and liberal arts fields.

Our education system needs to produce people who can innovate. At the beginning of the innovation chain are the idea generators—those who create new products, services and business models. Innovations can come from those who push the boundaries or frontiers of a given discipline yet further; or from those who fuse unusual features of multiple disciplines to come up with something also wholly new. We have called the former "Deep Divers" and the latter, "Interdisciplinary Connectors." Both are necessary for a vibrant innovation economy.

While these are not necessarily two different sets of individuals, they definitely reflect two different educational philosophies. Both exist in our present system, but not side by side. The cultivation of deep divers occurs almost exclusively in higher education. In college, and continuing into graduate school, the requirement to "choose a major" leads to a defined sequence of courses, qualifying exams, and thesis requirements that take one ever deeper into a subject area. By the conclusion of a Ph.D. thesis, a student is, by design, the world's solo expert on a particular micro-topic (the one in which he performed original research). In Chapter 7, we discuss how to change higher education so that an educational path for interdisciplinary connectors can exist alongside the one for Deep Divers.

In K–12, the educational philosophy, in contrast, tilts towards breadth rather than depth. K–12 is structured to prepare students "for life." As a result, it requires students to cover many topics—from "health" (nutrition and sex education) to American history (to inculcate civic awareness) to art (to stimulate creative expression)—that are deemed beneficial to the whole person.

… the opportunity for a budding scientist or engineer to lose himself in his or her passion, to become a "Deep Diver," is usually stymied, even in good high schools. K–12 students do not choose majors, much less the significant majority of their courses. Instead, a plethora of distribution requirements and long lists of concepts that must be covered (e.g., as embodied in state standards) locks down the curriculum to a broad, fixed configuration.

In the best K–12 schools, such as those with project-based learning, or International Baccalaureate programs, the connections between and among these various topics are sometimes explored in enough depth to produce true interdisciplinary connectors. However, the opportunity for a budding scientist or engineer to lose himself in his or her passion, to become a "Deep Diver," is usually stymied, even in good high schools. K–12 students do not choose majors, much less the significant majority of their courses. Instead, a plethora of distribution requirements and long lists of concepts that must be covered (e.g., as embodied in state standards) locks down the curriculum to a broad, fixed configuration. Indeed, most students have little choice in what and how they learn. This is because the educational system is standardized with an increasing number of curriculum requirements and must, by design, ignore individual needs and interests of students.[335] In fact, the premise is that student interests and individual learning styles and strengths are at best secondary to the education process. In this current "mass production" model of education there is limited, if any, opportunity for customization or personalization of the learning process as student interests are treated as largely irrelevant to what "has" to be taught. Traditional schools do not easily permit students who develop a particular interest to pursue that interest, no matter how strong the motivation or how useful the learning that might result. And the dominant direction of education reform is going even more strongly in this direction, based on the view that improving high school education is to require even more courses and even more subject-matter-based standards. The result, as the National Science Board recently wrote, is that "the U.S. education system too frequently fails to identify and develop our most talented and motivated students who will become the next generation of innovators."[336]

As discussed in Chapter 4, this rigid focus on learning a wide array of subjects is not required to provide the skills needed for students to effectively contribute to the economy. Moreover, it is also detrimental to creating both better and more STEM students as it limits students who are interested in STEM and able to become working scientists or engineers from pursuing their interests and passions. It's not just budding scientists and engineers who are disadvantaged by this system, but a large share of high school students. Nearly one-third of high school students drop out before graduation and nearly half of those point to boredom and lack of interest in classes as a reason for leaving school.[337] Given the lack of choice high school students have in shaping their own education, such numbers are perhaps not surprising.

MAKING ROOM FOR DEPTH IN K–12

Below we suggest some ways in which the K–12 school system, without losing its inherent ability to create interdisciplinary connectors, can also accommodate and cultivate the "Deep Divers" we need for our innovation economy.

The "Core" of What K–12 Students Really Need to Know is Actually Quite Limited

As discussed in Chapter 4, there is a finite list of probably six to eight skills needed for most jobs; the three "Learn How to Learn" skills being prime among them. If K–12 graduation requirements focus on just the six to eight core skills, then high schools should be able to produce "generic" high-quality employees by graduation, while minimizing required courses along the way. This then opens up opportunities for deep divers and those passionate about a subject, to explore it more fully in high school. Long sequences of courses in one topic become possible. So do courses that reflect unusual combinations of interests. Driving this new era of skills-centric learning in high school would enable high schools to become a system of mass customization, rather than one of mass production. A mass customization model would allow high school to tailor what is learned around the interests of students, provided that they learn certain key skills and competencies.

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Unfortunately, having higher but, fewer standards is no guarantee of fewer required courses, and therefore no guarantee that deep divers will emerge. A cautionary tale lies in No Child Left Behind (NCLB), which puts substantial emphasis on teaching just two subjects: math and English. Nevertheless, this emphasis did not result in brilliant mathematicians and authors spilling forth from our schools, over nine years, or Deep Divers in other subjects, either. Why not? The answer is, in part, that there was no concurrent reduction in the state-mandated requirements for graduation.[338] Elementary and middle schools were being asked by the federal government to do more in teaching math and English, but state laws that required teaching history and science, for example, were still on the books. School districts could not do both, so advanced classes in many topics, including math and English, were dropped, alongside "non-essential" classes in art and music. Thus, students who really wished to excel in English did not have the option to pursue creative writing, journalism and other classes necessary to further their talents. "Deep Divers" in math were similarly affected; computer science, which would have taught symbolic logic, was dropped from many sets of course offerings. Art students were often out of luck entirely.

The lesson to be learned from NCLB is that adopting new standards even if they are few in number—must be paired with dropping old requirements. Otherwise, the system ends up structurally and financially unable to meet all its obligations. Dropping old requirements gives school systems the breathing room they need to adapt successfully to new accountability requirements, while maximizing, as best they can, what they are able to offer students. The same holds true from the student side: new requirements (in this case, meeting skills standards) will need to be paired with dropping old requirements, in order for students—and particularly Deep Divers—to have the flexibility to tailor their curriculum to their needs and actual interests.

Relax Breadth Requirements Overall

Presuming that, in this new paradigm, a few essential workforce skills could become the centerpiece of high-stakes testing, what kinds of curriculum breadth requirements could be simultaneously dropped? The answer is, most of them.

Writing and reading are clearly core skills, as identified by all groups (employers, skills coalitions, skills assessors). Thus reading and writing in some form are nearly guaranteed to remain in a skills-centric curriculum. However, high school English is usually taught as literature analysis, and it is not necessary. While analysis may ultimately end up being voted a "key workplace skill" by employers, it can be taught in many contexts, ranging from philosophy, to logic, to English to math.[339] Students should be in the position to choose which, based on their primary interests. The "Learn How to Learn" skills, once taught well, eliminate the need to require most knowledge-centric courses, which include much of history and civics/government.

Art and music, though they add to the enjoyment and appreciation of life, are not workforce survival skills for most people. Foreign languages likewise are highly useful, but not essential for most workers. Already we have pared down the high school curriculum requirements to the point that the next budding Edison or Einstein should be able to take eight courses in math without worrying about taking art or history. And, equivalently, the next Picasso could take eight courses in art without worrying about biology.

At such an early point in their lives, most students are not obsessively focused on a single topic and will continue to take a blend of subjects that interest them. That is not only an acceptable, but a beneficial outcome. Some of these individuals will become interdisciplinary connectors, moving back and forth between two or more fields throughout their careers. Some will come to their true callings later in life, but make wiser choices having been exposed to the alternatives. And, if a student misses a particular content area in high school, it is not the end of the world. The skills they need to support themselves will be in place. The chance to take a ceramics class will always be there, even as an adult. The chance for an artist to wonder at fractals and read up on chaos theory will also always be there—once the foundational learning skills are present.

In terms of process, the steps for paring down breadth requirements should begin after key workforce skills are defined by a national panel of employers. At that time, the National Governor's Association can begin to coordinate state-level dialogues that eventually lead each state to arrive at a much smaller set of core requirements for graduation. Useful inputs for that process—which can be gathered in the interim—would be a series of test scores reflecting increases in key skills among students before and after taking a particular required class. If the class does not significantly advance one of the key skills, it should be on the "hit list" for elimination from state graduation requirements. The three "learn how to learn" skills are prime metrics by which to screen an initial set of courses, since tests for these skills already exist and are already being implemented statewide in some cases.

Relax Breadth Requirements in Math and Science

Given that the purpose of this report is to identify ways to change educational institutions to produce more and better STEM students, it may surprise the reader to find this report advocating that math and science requirements also be cut, in addition to those in art, history, civics, language and other subjects. There are several reasons for this.

First, science requirements need to be cut in order to give students the freedom to explore their passion and future career skills. Only a very small portion of the U.S. workforce works in STEM. Other people need different kinds of pre-career training. In the Conference Board Survey only 9 percent of employers cited science as "very important" to the skills they looked for in high school students.[340] This is consistent, in order-of-magnitude, with the small fraction of the general workforce working in STEM.[341] While science advances a certain fundamental skill (inquiry), not everyone needs that skill. Moreover, that relevant skill can be gained through any science class. At most, one high school science class should be required for graduation, with no restriction on which one. The three science course areas typically prescribed for graduation—biology, chemistry, physics—are there for no other reason than historical precedent.

But, the most important reason that STEM graduation requirements—and particularly distribution requirements within STEM—need to be cut is to allow students interested in STEM to be able to specialize more. The requirement to take four high school science courses, with three of them (physics, chemistry, biology) typically prescribed, prevents even students passionate about one of those subjects, from pursuing it further. STEM deep divers who must take biology, chemistry and physics, often cannot take both advanced biology and biochemistry in addition, even if that's where their interest really lies.

Worse yet, the three to four science courses mandated in most high schools crowd out the ability of schools to offer students other STEM courses. How ironic that engineering and IT together employ 80 percent of STEM workers, yet are nowhere represented in the K–12 curriculum. Occasionally, cries for change are heard: for engineering, the National Academy of Engineering released its report, "Engineering in K–12 Education: Understanding the Status and Improving the Prospects." The Engineering Education Act ("E-Squared" for Innovation Act) was subsequently introduced to provide funds to states to help integrate engineering education into K–12.[342] Yet, public awareness is low, and action nonexistent.[343] Computer science also strives to be heard: this year, the Computer Science Teachers Association had to suggest to the Department of Education, after the fact, that computer science be included in the language of the Race to the Top grant opportunity.[344] Apparently, being "top" in the world's education system currently means not teaching computer science.

> **But, the most important reason that STEM graduation requirements—and particularly distribution requirements within STEM—need to be cut is to allow students interested in STEM to be able to specialize more. The requirement to take four high school science courses, with three of them (physics, chemistry, biology) typically prescribed, prevents even students passionate about one of those subjects, from pursuing it further.**

Some, but not all, math classes can also be deleted from graduation requirements. With respect to mathematics, algebra and geometry are fundamental to many occupations, ranging from construction to graphic arts—and would still be required even in a skills-based paradigm. However, trigonometry is debatable, and calculus is actually quite specialized knowledge. Very few people use calculus on a daily basis in their work—compared to the near-universal use of statistics, both inside and outside of STEM (indeed, ACT tests only statistics, algebra, geometry, and basic computational math in their key workforce skill for "applied mathematics").[345] We therefore suggest calculus not be mandated for graduation. This then opens up the opportunity for STEM students to take advanced statistics or computer science instead. There is little to be lost by not mandating calculus, since most colleges offer calculus the freshman year, for those who need it, including STEM students. Precalculus/trigonometry is a slightly different story. Though not really necessary as a core workforce skill, eliminating it as a graduation requirement will add an extra year or an extra summer to a non-STEM major who wishes to turn into a STEM major in college. Lack of precalculus/trigonometry also negatively affects college admissions chances for some students in the present system. Thus, we recommend that trigonometry/precalculus may need to be retained in K–12 graduation requirements until such time as more of the national education system has begun to re-establish itself along a skills paradigm, at which point its true value can be sorted out.

Generally speaking, math is more important to include in graduation requirements than science. It is far more central to more occupations. It also builds linearly on itself in such a way that missing one year early on handicaps the student into the future. Missing algebra means having to make up three to four years of math subsequently in college. Missing biology means having to make up just biology, and even then, only if one's college major requires it. We therefore advocate asymmetric requirements for math and science, with more math required for graduation than science.

How ironic that engineering and IT together employ 80 percent of STEM workers, yet are nowhere represented in the K–12 curriculum.

Institute Competency-Based Credit Systems

Minimizing distribution requirements is a workable approach to giving students the "space" they need within the curriculum, to explore their chosen passion in depth. A second way forward, which should occur in parallel, is to allow students to gain academic credits through proficiency rather than seat time. Students can then unclog their schedules by testing out of skills or subjects they already know and taking any classes in high school that they are interested in and capable of doing the work in, regardless of their class level.

The general principle is that students should be allowed to receive credit for a single course or set of courses with an equivalent competency assessment. For example, if a student achieves a 4 or 5 on the English ACT, he would not have to take any more high school English and could replace those courses with any elective desired. Similarly, if a student takes and passes the entire senior graduation exam as a junior, all further required courses would be waived, allowing all subsequent courses to be electives.

This competency-based system incentivizes students to try to achieve more, earlier in their high school career. They can avoid classes and teachers they dislike by learning the material on their own, which is ultimately the skill that they need to have. They can also open up space for other courses they want to take, by completing mandated courses early. With open courseware and other supplemental materials available via the Internet, this is increasingly possible. Gifted and/or highly motivated students would not be required to sit through classes they have already mastered and would be freed to take deeper, more meaningful offerings—or explore new areas entirely.

To date, few K–12 school systems make any use of competency-based credit. An exception is Alabama, which in 2008 passed a law enabling "Credit Acceleration and Credit Recovery." The Alabama system allows the student to skip directly to taking the end-of-course test, and receive credit that way. However, the local school can lose funding under this approach, in that it does not receive any financial compensation for students who end up graduating early, as a result of mastering all their credits in fewer years.[346] Replacing seat-based school funding formulas by competency-based funding formulas avoids this problem.

To remedy this, ideally states would legislate competency-based credit systems in conjunction with a competency-based school funding model. In the latter, schools are paid, not on the basis of student attendance hours (seat time), but on the basis of successful completion of course credit units (either by students taking opt-out tests or by completing conventional classroom instruction with a passing grade). In states where school funding is primarily the responsibility of the local government or the local school district, it is these other entities that would have to move to a competency-based funding model.

Currently only the Florida Virtual School receives course funding based solely on successful student course completion: their funding formula from the state includes no reference to seat time, only course completions.[347] The funding formula does include a percentage of additional funding to cover costs of students who cannot or do not complete coursework (since some of these costs are real and cannot be completely avoided; e.g., families changing school districts will lead to incompletions that are no fault of the school).[348] According to a quantitative analysis by the Florida Tax Watch Center for Educational Performance and Accountability, the Florida Virtual School not only delivers educational outcomes that are better than the Florida public school mean (e.g., 26 percent higher performance on tenth-grade state math exams and outperformance of traditional students on AP end-of-course exams), but also serves the students using a more cost-effective method for the taxpayer, about $1,000 per student cheaper.[349] The unique funding model as well as the student-centered approach of denying no student access to take a Florida Virtual School course if academically appropriate, is what enabled the rapid growth of Florida Virtual School (25 percent per year), to serve 154,125 students in 2008–2009.[350]

Competency-based or performance-based funding incentivizes the school to ensure its students pass their subjects with proficiency and mastery, as opposed to having students simply sit in a classroom. As such, it is the institutional incentive that complements the student incentives provided by competency-based credit systems. For most students and most schools, this funding paradigm opens up a great deal of flexibility in what is learned, when, and how.

We propose that school funding authorities emulate the successful Florida Virtual Schools competency-based funding model for all schools. Under competency-based funding, the temptation for schools to issue vacuous credits to failing students exists, but it can be avoided by simultaneously requiring meaningful state graduation exams or other enforceable accountability measures. With this external constraint, schools that might be tempted to pass poor performers in order to receive funding cannot do so. In this situation, the school would be driven to find an external solution for those students (e.g., find and pay a remedial skills provider with a strong track record). But, at least external solutions are now possible; the school loses none of its own funding for the following year by outsourcing the student to another provider, as long as the student can then pass the school's end-of-course (or state's end-of high school) exam. In the end, such outsourcing may prove to be a better solution than keeping unwilling or disruptive students in the classroom.

… the Florida Virtual School not only delivers educational outcomes that are better than the Florida public school mean but also serves the students using a more cost-effective method for the taxpayer, about $1,000 per student cheaper.

A case study of how to manage poorly performing students in a competency-based credit/funding system based in the Weld and Larimer Counties of north central Colorado offers at-risk students a self-paced, Internet-based program of study offered by Aims Community College.[351] Of the $5,000 per student that the home school receives from the state, it pays $4,300 to Aims to provide instruction. Aims, in turn, spends $2,315 per student to educate these students, meaning both the home school and the Internet course provider benefit. Students take no formal classes nor do they receive any Carnegie units/credits while taking the Internet study sequence. They do, however receive a high school diploma from their home school if they can pass nine WorkKeys tests at the end, with scores equivalent to those of a solid beginning college student. Over the past ten years this program has resulted in an 80 percent graduation rate of the at-risk students. Fifty-six percent go on to community college, 23 percent go onto the workforce, and 8 percent enter the military. Because of its success, the Weld-Larimer/Aims program has grown from 10 slots per year to 370 slots per year. Marsha Harmon, the director of the Aims Community College—Weld/Larimer County High School Diploma Program, notes that 30 percent of the at-risk students test in as "gifted," but are just too impatient to stay in school.

If both competency-based credits and competency-based funding can be accomplished, then we will have opened the doors to a new era in high schools, one in which knowledge flourishes in many forms, because the focus has shifted from occupying a seat and acquiring a fixed set of knowledge, to achieving proficiency in certain skills. This will allow students to practice and develop those skills across a wide array of content or knowledge areas of their choosing.

ENSURE QUALITY EDUCATIONAL EXPERIENCES ARE AVAILABLE TO ANY DEEP DIVER

Giving students an uncrowded curriculum in which they can explore their chosen interests, is the first step to creating Deep Divers. This can be accomplished by moving to a skills-based accountability system that requires only a few things be taught thoroughly, by slashing most courses from state graduation requirements (but not from the schools themselves), and by adopting legislation that allows students to "test out" of courses they have mastered, without having to take them. This last step is further facilitated by competency-based school funding models in which schools are not penalized if the student master's the material but does not occupy a seat.

The final step is to ensure that students with free time in their schedule, actually have access to the cornucopia of class offerings that would further stimulate and develop their interests. Two strategies suggest themselves. In the first, students move to content. This is the strategy embodied by the STEM schools approach. Advanced content is offered in a few locations, and students are physically brought to these locations. In the second strategy, Deep Diver content is moved to the student. Placing a small army of STEM specialty teachers in every high school, while one of the most popular STEM policy recommendations, is very expensive and difficult to accomplish and not likely to be implemented for both reasons. Instead it makes more sense to borrow the content and/or experiences from elsewhere, and deliver them to schools by piggybacking on existing

distribution networks. This is the strategy embodied in the K–12/community college partnerships, early college high school, and dual credit options; in proposed efforts to utilize products and distribution networks from commercial providers; and in the virtual schools approach—all described below.

Create STEM High Schools

By establishing new high schools that focus primarily on STEM subjects ("STEM high schools"), and enabling Deep Divers to enroll in them, we can target attention to those students especially interested in STEM and most capable of becoming STEM workers. This in turn, makes delivery of rich course offerings to those students not only more cost-effective, but also more effective.

Two students at the Science and Engineering Magnet in Dallas, Texas work on a chemistry experiment.

STEM high schools are publicly funded schools that offer more extensive, in-depth math and science coursework than is available in traditional public school. They also draw students from a larger geographic area than a traditional local public school, but are selective in their admission, typically using entrance exam scores complemented by grades, teacher recommendations, and essays to choose the entering class. Instead of just "chemistry, biology, and physics," these schools can offer topics like Biomedical physics, Immunology, Microbiology, Multivariable Calculus, Number Theory, Differential Equations, Math Modeling, Computer Programming III, and Web Application Development—to name a few classes available, for example, at the Arkansas School for Mathematics, Sciences, and the Arts. In some cases the schools operate as "schools within a school," offering these enriched classes to a subset of students located in the same physical building as a conventional public school. The latter arrangement has evolved in part as a means to achieve voluntary racial or socioeconomic desegregation because the STEM high school will pull students in from well beyond the locale served by the school in which it is housed.[352]

There are approximately 100 math and science high schools in the country, enrolling around 47,000 students. Few as they are, these schools do their job, as a recent ITIF report summarizes:[353]

> Ninety-nine percent of graduates enroll in college within one year of high school (compared to 66 percent nationally) while 79 percent complete college in four years (compared to 65 percent in private universities and 38 percent in public universities).[354] Moreover, 80 percent of graduates of STEM high schools intend to earn a master's or doctorate degree,[355] while just 10 percent of 30-year-olds have a graduate, professional or doctorate degree, while 53 percent of students among those in the highest quarter of family SES are expected to complete graduate or professional school.[356]

STEM high schools are also cost-effective means of developing Deep Divers. Indeed, the UK equivalent, the specialist school, was born out of a late 1980s budget dilemma of how to pay for technology education, given the expense of equipping all schools with computers.[357] The solution was to create "specialist schools" focused on the delivery of technology education. In the UK, "All STEM for Some" turned out to be cheaper than "Some STEM for All." Today over 90 percent of English high schools are "specialist schools" of one kind or another, with specializations ranging from arts and humanities to engineering to sports to business.[358] Those interested in art, go to arts schools; those interested in STEM go to technology, math & computing, or engineering schools. All schools cover the minimal national curriculum requirements.[359] But the division of advanced resources, beyond the minimum, is very cost effective. It allows the sports school to have the new stadium, and the science school to have the new laboratory, without having to pay for a new stadium and a new laboratory for both schools.

Focusing specialty STEM courses into a few—rather than all—schools has the additional advantage of attracting follow-on corporate support. It is much easier for a technology company to donate goods and services to 5 schools than to 500. For example, one of the nation's premier STEM high schools, the Thomas Jefferson High School in Alexandria, Virginia, has received donations from Google, Northrop Grumman, Raytheon, Cray, Sun Microsystems and others.[360] The UK specialist system actually requires sponsorship of 50,000 pounds to launch a specialty school, of which at least 15,000 pounds must come from outside of the school community; this ensures corporate interest from the start.[361]

A related model is STEM-focused career academies. Career academies can be programs within existing high schools or stand-alone institutions. While students complete regular high-school coursework, they also are exposed to specialized curricula related to specific careers. In STEM, there are career academies focused on IT and Engineering. For example, the Academy of Engineering is a group of 13 pilot schools that focus high school students on careers in science, technology, engineering, and mathematics. Most are urban schools serving underrepresented minorities.[362]

One criticism of STEM high schools is that they are not racially diverse. Thomas Jefferson High School, while an academic role model, has a student body that is 41 percent Asian and 47 percent White, but just 3 percent Hispanic and 2 percent Black while the surrounding area of Fairfax County is 16 percent Asian, 72 percent white, 14 percent Hispanic and 10 percent Black.[363] But this criticism misses three key points.[364]

First, the goal of STEM education in high school should be to produce the best STEM graduates to fuel the innovation economy, regardless of ethnicity or socio-economic status. But even leaving this aside, allowing students to more actively pursue their own interests should increase retention among all groups, including disenfranchised groups. The gifted-but-bored minority student, who finds European history next to useless, may remain longer in school, if allowed to pursue an engineering class where it is possible to actually do something. Those students will come from a variety of backgrounds. But one reason we don't have as diverse a pool of students is that we have not focused with laser-like precision on finding those students interested in STEM. An aggressive middle-school recruiting program would give this advantage.

This is not to say that efforts should not be made to cast a wide net for STEM high school enrollment. In fact, a system where STEM resources are focused on a few high schools needs to be accompanied by an aggressive recruiting system for STEM talent that reaches well beyond the "usual suspects" and into all middle schools, and high schools. This assures that all who have evidenced either an interest or capability in STEM are directly informed of all the opportunities that are available to them, including that of going to a free STEM high school.

It may be worth establishing more STEM grade 9–12 boarding schools as well. This would make in-depth STEM education, in a safe and well-provisioned environment, available to a much wider audience than a bus commute radius would typically allow. The track record of some free boarding schools can be very impressive. For example, the SEED school in Washington, D.C., which is foundation-supported, is a (non-STEM) boarding school that serves the urban poor. Ninety-seven percent of each graduating class is accepted to a four year college, and 75 percent of those are the first in their families to attend college.[365] This model has now expanded to Maryland, which launched its own SEED school using government funds in 2008.[366] Development of similar boarding schools with a STEM emphasis would not be a far stretch.

The gifted-but-bored minority student, who finds European history next to useless, may remain longer in school, if allowed to pursue an engineering class where it is possible to actually do something.

Because they are an efficient means of creating and reaching Deep Divers, we recommend Congress allocate $200 million a year for ten years to the Department of Education to be supplemented by states and local school districts and industry with the goal of increasing by a factor of five the number of STEM high schools to 500 (up from around 400 now) and enrollment to around 235,000 by 2015.[367] A similar recommendation by the President's Council of Advisors on Science and Technology (PCAST) estimated that the Department of Education would need to provide financial support totaling at least $10 million per high school for planning, professional development, materials, laboratories, technology, and equipment.[368] Under this proposal, the federal government would provide no more than half the funds.

In addition, institutional partnerships are a key to success of STEM high schools. Whether it's the donation of research equipment, the opening of facilities to students and faculty, or mentoring of students, technology-based companies can play an important supportive role. To further their involvement, Congress should modify the research and experimentation credit to allow companies to take a flat (non-incremental) 30 percent credit for donations of equipment to high schools.

If Congress does not want to allocate funds for the creation of these additional schools, it could tie the receipt of existing federal education dollars to the establishment in states of a certain number of STEM high schools depending on the size of the state. The disadvantage of this approach is that states will respond solely to retain federal support. In contrast, with the additional funding model, states and local school districts that are most motivated to creating excellent STEM high schools will be the ones most likely to apply. Expanding STEM high schools in this way will enable slightly more than 1.5 percent of all high schoolers or about one-third of future STEM practitioners to specialize in STEM.[369]

In the absence of—or as a complement to—federally-supported STEM schools, states can create their own STEM high schools. For this, we recommend states follow the model of Minnesota's proposed NewSchools organization, a 501(c)3 non-profit that raises and directs public, as well as private, resources, to support "innovative" schools, sets binding policy for those schools, and is responsible for executing directives from the legislative and executive branches, with respect to these schools. STEM high schools and high schools centered on project-based learning (see Chapter 5) would not be the only schools created under such a model; indeed, the chance to work under a system with far fewer of the existing regulations, processes, and procedures opens the door to alternative teaching methods, alternative evaluation criteria, alternative budget allocations, and alternative course requirements of all kinds. In short, it would open the door to virtually everything that is needed to implement the STEM high school model proposed here, or a project-based learning intensive school (whose subject matter may or may not be STEM).

Make Advanced STEM Education Available via K–12/Community College Partnerships: Early College High School, Dual Credit Options

At first glance, making advanced offerings in STEM available to a widely distributed audience of Deep Divers seems to require outfitting numerous local high schools with expensive facilities and hard-to-find teacher experts. One solution is to concentrate students interested in specializing in STEM in fewer schools, as described above. Another is to take advantage of buildings, teacher corps, curricula and lab facilities that are already in place—in local community college systems. High school Deep Divers could take more specialized STEM courses in the local community college if transportation is provided, and the courses they take could generate credits towards graduation. These kinds of curriculum sharing partnerships between high schools and community colleges are already beginning to flourish in the form of Early College High School and Dual Credit systems.

Early College High School now operates in 200 schools in 24 states.[370] In this program, high school students are bused to a local college for all or part of their last two years' curriculum. These students earn their final two years of high school credits concurrently with the first two years of college credits; the more ambitious students receive their high school and Associates' degree at the same time, upon graduation. The Early College High School approach costs school districts about 5 percent to 12 percent more to operate than the cost of a traditional public school.[371] However, because it counts as part of the student's K–12 public education, it is free to the student. Indeed it saves money for the student overall, since students can spend less time in college.[372] An Early College High School would be the more formal approach to allowing Deep Divers access to STEM topics at a local college. It identifies a unique cadre of students and offers them an integrated two years of curriculum with attached support services. A less structured model is the dual credit system. In the dual credit approach, a student also receives simultaneous high school and college credits for courses taken at a local college. However, the dual credit courses are individual offerings taken whenever and however the student's schedule allows. Because it is simpler to implement, about 71 percent of public high schools currently offer dual credit courses.[373]

Each model has its strengths. The Early College High School model is more structured and would probably lead to greater persistence among Deep Divers whose home and/or school had few academic supports. In fact, the Early College High School model, as it is presently constructed, is designed primarily to move low-income students into college. It was not designed to give these students access to unique courses or facilities—though it does this too. Presently, 59 percent of Early College High School Programs' students qualify for free or reduced-price lunch, 70 percent are students of color, and 86 percent go on to some form of postsecondary education upon graduation.[374] One reason for the high-school-to-college transition rate of Early College High school students is that this model decouples college academics, which many low-income students are capable of handling, from college processes, which can present impassable gates (e.g., filling out FAFSA forms is the primary limiting "gate" for college transitions among Hispanic students).[375] For STEM Deep Divers from low-income areas, a "STEM-specialized" Early College High School model may be the optimum approach, as it would not only provide advanced subject matter exposure in STEM, but also eliminate a major barrier in the high-school-to-college transition.

The dual credit system, being less structured, offers more flexibility but fewer supports. It is well suited to advanced students in high schools who are reasonably well off, but who lack advanced curricular choices. It is particularly popular in large suburban high schools in the Midwest/Central areas of the United States.[376]

The federal government is well positioned to encourage the spread of both these models. In particular, the U.S. Department of Education could partner with the foundations currently supporting Early College High School Programs (The Bill & Melinda Gates Foundation, the Carnegie Corporation of New York, the Ford Foundation, the W.K. Kellogg Foundation, and others) to incorporate a STEM track within existing programs, or to launch new Early College High School Programs with a STEM focus—particularly in locations where low-income neighborhoods are fortuitously located adjacent to strong STEM colleges and universities.

With respect to dual-credit systems, the largest hurdle is their uneven implementation. Small high schools, rural schools, urban schools, schools in the Northeastern United States, and schools with a greater minority enrollment offered dual credit options less frequently than other schools.[377] The reauthorization of the Elementary and Secondary Education Act provides an opportunity to encourage the spread of dual credit systems by establishing numerous, but small ($5,000 to $10,000) grants that would give startup funds towards the establishment of dual credit courses. Grant applications would have to be co-submitted by a high school and a college, partnered together. The two would have to offer a minimum of 10 credit-bearing courses, co-listed at both the college and the high school, to be eligible for the grant. The funds could support administrative expenses required to implement a dual credit system (e.g., redesigning enrollment software to allow cross-over registration) or transportation services (shuttle service to the local college). Funds could not be applied to teacher salaries, since the objective is to leverage off of existing resources.

Make Advanced STEM Education Available via the Nation's Virtual Schools

The easiest way to reach large numbers of students who are geographically dispersed is through online learning. U.S. online learning is growing rapidly, at a pace of 30 percent annually faster than any other innovation in K–12 education. Forty-five states now have some form of state-funded online learning. Twenty-seven states have full time online/virtual schools (e.g., Florida Virtual School, Georgia Virtual School, Idaho Digital Learning Academy) and 25 states allow enrollment in full-time virtual school programs. In thirteen of these states, virtual school enrollment is expanding at a rate of over 25 percent per year; for New Mexico and North Carolina, the expansion rate is over 50 percent per year.[378] School districts offering online courses abound, including those in Los Angeles, Fairfax County, Virginia and New York City. Charter schools also provide full-time online learning opportunities in 25 states. Examples are the Colorado Virtual Academy, the Commonwealth Connections Academy, and Insight Schools and IQ Academies in Wisconsin. Overall, there are an estimated 1.5 million enrollments in K–12 online courses in 2010 and the numbers are expected to continue to increase.[379]

Even despite strong growth rates, the demand for online courses is still outpacing the supply in K–12 education. Surveys such as Project Tomorrow show that more than 40 percent of middle- and high-school students would like to take an online course, and 47 percent of parents want their sons and daughters to take an online course prior to graduating to prepare them for the future.[380]

> **… more than 40 percent of middle- and high-school students would like to take an online course, and 47 percent of parents want their sons and daughters to take an online course prior to graduating to prepare them for the future.**

Because online education is growing so rapidly on its own, and because states intentionally design virtual schools to access rural and underserved areas, it is an ideal infrastructure by which to reach out to STEM-hungry youth who may not otherwise have the opportunity to participate in a high-quality, or in-depth STEM curriculum. Other populations, such as home-schooled students, would also benefit.

The Nature of Online STEM Learning and Virtual Schools[381]

According to the Department of Education, the primary reason online courses are offered is to expand offerings to courses that would otherwise be unavailable.[382] Online courses are prevalent in 75 percent of school districts primarily to compensate for teacher shortages in hard-to-fill subject areas, such as science, math, or Advanced Placement (AP) courses.[383] They are a "necessity is the mother of invention" response. Thus, because 40 percent of our nation's high schools do not offer Advanced Placement, 50 percent of the online courses offered in high schools are AP and dual-enrollment classes.[384]

Online K–12 offerings in STEM include such popular standards as Algebra I, Biology, Chemistry and Physics, as well as specialized electives, such as AP Environmental Science, Biotechnology, Computer Science and Engineering. As one example, the State of Georgia has 440 high schools, but only 88 practicing licensed high school physics teachers. Online physics courses allow every student in Georgia who is interested in physics to sign up for a high school physics course through the Georgia Virtual School, despite the severe shortage of qualified teachers and regardless of where the students live or what their income level is. The instructors in the online school are also Georgia-certified with physics credentials, but hold adjunct status—i.e., they have fewer privileges such as tenure but more flexibility in time spent teaching and the location from which they teach. Thus online learning expands the available teacher pool as well.

Online learning is also growing as a means to transfer advanced content from colleges and universities directly into high schools. For example, the University of Montana will soon be home to Montana's state virtual school program, through which it can offer K–12 online courses statewide, and help prepare pre-service teachers in online instruction within the College of Education. The University of North Carolina at Greensboro now provides online dual enrollment courses to students in high school across the state so that juniors and seniors in rural North Carolina are able to access courses in school libraries and computer labs to begin earning college credit. Northwestern University and Stanford University, in their programs for gifted youth, now offer university-led online learning programs in STEM, designed for high school students.

The online environment can operate in loco scholae (in place of the school) and provide in-depth experiences beyond what is possible in traditional classrooms. Teachers now use online connectivity to engage in discussions with distant NASA scientists and Nobel laureate physicists. State-of-the-art laboratories at research universities can be brought directly to the student via iLabs.[385] This National Science Foundation-funded project allows expensive, modern laboratory equipment housed in universities, such as Northwestern and Massachusetts Institute of Technology to be networked for access by K–12 educators and students who wish to conduct authentic scientific investigations. In iLabs, real experiments are performed via the Internet by students utilizing such web-networked scientific tools as high-powered microscopes, telescopes and other equipment. Students operate controls remotely through a local computer. The system allows them to use investigatory processes, equipment, data from the experiments, and expertise that are not available in most schools today. One can calculate that if a standard laboratory experiment is about three hours in duration, and a piece of equipment is available via iLabs at least eight hours a day, then 666 laboratory sessions are available to students in different locations over a 50-week school year. If the equipment is available 24 hours a day, and students are allowed to work from home, then the number of sessions triples; effectively two to three high schools can share one piece of equipment on a rotating basis. iLabs does not obviate the need to buy equipment, but it does limit the need to buy as much equipment, and it is a workable solution for schools whose budget has little room for capital purchases.

Learning Outcomes

The fact that well-designed online experiences can produce significant learning outcomes is demonstrated in K–12, college, and corporate environments. In K–12, Florida Virtual School (FLVS) students outperform bricks and mortar school students by about 39 percent across the sixth-grade to tenth-grade state math exams. Even better results are achieved for reading. This is not a result of a difference in the types of students served; the FLVS demographic is very similar to the state's overall demographic.[386]

Online learning is also effective at the college level, which bodes well for the new trend of using online learning as way to serve both college and high school students simultaneously. An example is Carnegie Mellon's open learning initiative, which attempts to leverage the best technology with the best pedagogical approach embedded in instructional design. The Carnegie Mellon online statistics course, StatTutor, yielded learning outcomes that were identical to its best in-class learning experience, and significantly better than the national average learning experience: StatTutor students achieved <g> score- type gains of almost twice the national average on the CAOS (Comprehensive Assessment of Outcomes in a first Statistics course) test.[387] Blended instruction (online + in-person) proved to be particularly powerful; in this mode, StatTutor students achieved CAOS <g> scores of about 0.4 (on a scale of 0 to 1), compared to CAOS <g> scores of 0.06 for a control group exposed to lecture alone, and did so in half the time. Research reviews also show that student performance in online and blended learning is as good as or better than face-to-face, based on increases in student achievement.[383]

How Learning Takes Place in Virtual Schools

Virtual schools are a specific formal systems approach to delivering online learning, where everything from teacher preparation to enrollment policies to the monitoring of cheating are designed with virtual delivery in mind.[389] Virtual schools provide a student-centered experience. Enrollment is often open, so students can begin a course at any time. The "textbook" is typically an interactive website that may contain advanced simulations to explore, and workbook-type questions to guide the learner's thinking. Students are usually required to email/upload written assignments on a fixed schedule, once they begin a course, but the hour of the day in which they do the work, the pace, and the order of learning is up to them. Discussion forums allow students to interact with other students and with the teacher. Field trips are scheduled with groups of students to interact and explore museums and experiential learning that complement course work.

Without the need to present or attend lectures, there is much more time for student-teacher discussion in a virtual school than in a bricks-and-mortar school. In the virtual school, the teacher calls the student on the phone or holds one-on-one or group sessions through synchronous software tools frequently to ascertain progress and answer individual questions. Thus, the online teacher is less of a lecturer and more of an individual one-on-one tutor, facilitator and coach.

Laboratories exist in virtual schools as well. They may be conducted using remotely controlled equipment, in-person visits to nearby facilities (e.g., local community college) or—most commonly—carried out in the student's home, using readily available materials or a kit mailed by the virtual school. Given the ever-present concerns over student safety in high school laboratories, most common experiments are designed to be safe enough to be conducted at home, often with the kitchen counter as a lab bench. The list of innovations in virtual schools is long-it is clear we are embarking on a reconstruction of the entire learning system, not just utilizing a new vehicle for delivering the same content and process.

While the primary reason online courses are offered is to expand offerings to courses that would otherwise be unavailable, the second most commonly cited reason for offering online learning is to meet individual student needs.[390] This personalization is enabled in part by allowing student choice and flexibility in pacing, a convenience epitomized by the Florida Virtual School slogan, "Any time, any place, any path, any pace." However, personalization is also facilitated by teachers' unprecedented access to data on student learning. Indicators of the pathway by which students are learning include student discussions with other students online, improved access to outside resources and links, how course content is accessed and used, availability of multimedia learning tools, practice quizzes, and others. These support the student by helping the teacher to individualize instruction, and along with data from assessments, assignments, presentations, projects and tests, provide a more complete picture of student competencies. Teachers therefore can reconstruct not only what students know, but the pathway by which they came to know it, and offer multiple pathways. In the future, mass customization and increased personalization in online learning will be facilitated as artificial intelligence supports advances in adaptive content and adaptive assessments, and recommendation engines funnel student learning preferences into learning contexts that are most relevant with customized content. Ultimately, each module of information will be deliverable in multiple formats and platforms, each tailored to best meet the needs of a particular student at a point in time. New contexts available for content delivery include gaming, virtual worlds, social networking and mobile learning, as well as student-centered communities of practice emerging on the web.

Using online learning in combination with face-to-face instruction—an approach termed blended or hybrid learning—is now emerging as an important trend across K–12 and higher education. Allen and Seaman define a blended or hybrid course as a having 30 percent to 79 percent of its content delivered online, typically using online discussions, online content, and/or an online learning-management system, with the remainder of the instruction provided face-to-face.[391] Blended learning programs may be in a buffet model, where students take four or five classes traditionally and then take one or two classes online; or, in the emporium model, where a class uses blended courses as described above. The education community appears to be reacting positively to the blended learning trend. According to a 2004 Educause Research Bulletin, "combining face-to-face with fully online components optimizes both environments in ways impossible in other formats."[392]

Making Virtual Schools Available to Deep Divers Everywhere

Most states' virtual schools are designed to serve the needs of in-state students first and for free; typically, any student in any school in the state is allowed to take the classes so offered, with credits transferring to their bricks-and-mortar school just as if they were transfer credits from another high school in the state. However, virtual schools will also take out-of-state students for a fee. Therefore, in the current system, innovations and deep content that exist in any virtual school are available to students in any state, but for a fee.

Several policy changes are needed to ensure more widespread availability and use of virtual courses. One problem that exists today is that states may not recognize a course taken out of state as counting toward requirements for graduation. To remedy this, the Elementary and Secondary Education Act should include a reciprocity mandate that requires schools to give students credit towards graduation for courses taken at virtual schools if the same virtual courses/classes are recognized and credited towards graduation in another state. Thus, if "English Fantasy Literature" counts as an English credit in Alabama, a student in Texas who takes it would receive an English credit from his own school.

The second problem is with funding as states charge out-of-state students. There are several possible solutions to this. The first is for states to agree to compacts whereby they waive fees for out-of-state students if their state of residence also waives fees for their virtual courses. This would be similar to the "bill and keep" system telecommunications networks use where each network agrees to terminate calls from the other network at no charge. The second policy would be to adopt the competency-based model of funding. Once it is clear that the student's completion of an online course elsewhere must count towards in-state graduation requirements (as per the proposed federal law), then, in a competency-based funding model, the school funding authority must pay the home school when the student completes an online course.[393]

Competency-based funding actually presents a winning scenario for the bricks-and-mortar school, because the cost of educating a student in a virtual school is about 85 percent of what it is in a bricks-and-mortar school.[394] So, the home school pays 85 cents on the dollar to an out-of-state virtual provider for the student to take an online class, but then receives a dollar from its funding authority at the end of the year when completed student credit hours are tallied up. Private providers can also participate in this model; however, without a legislated reciprocity mandate, the competency-based funding model would require the student who has taken a privately-offered online course to take the in-class final exam to receive course credit, and for the school to receive its funding from the state, local, or school-district funding authority. Competency-based funding achieves additional flexibility for the student and the school at no net cost to the state/local/school-district funding authority.

In our view, competency-based funding is required for the seamless integration of online offerings alongside physical school offerings. At present, funding for online courses is forcibly re-engineered back into seat-time funding policies, which occasionally leads to absurd requirements, e.g., that the student must be learning online during a specific hour of the day, or a certain number of hours each week (regardless of the rate of progress). Competency-based funding is also necessary in order to pave the way for students to test out of classes they have already mastered. We therefore propose, once again, that state, local and school-district funding authorities adopt a competency-based funding models for the schools they support.

If all states can more easily avail themselves of each others' virtual school offerings, then any STEM learning innovation placed into the current network of virtual schools has the potential for extremely high penetration across all states. Because the potential leverage is enormous, we recommend that the federal government provide explicit funding, on the order of $10 million to $20 million annually, for STEM learning innovations appropriate to virtual schools. Products so developed must be available within the virtual schools network at a cost no greater than the maintenance cost of the software. However, the products could be repackaged for commercial sale outside that network. Intellectual property would reside with the virtual school(s) but could be assigned to the corporate partner, as allowed by the Bayh-Dole Act.

CHAPTER 7:

Creating STEM Interdisciplinary Connectors in College

A student at Olin College of Engineering in Needham, Massachusetts.

In Chapter 5, we argued that to move to an innovation economy, the United States requires not just more STEM graduates, but also STEM graduates with different kinds of skills. These include the Deep Divers, who push the boundaries of a given field, and whose educational needs were explored in Chapter 6. It also includes the Interdisciplinary Connectors, who create new products via the fusion of two or more disciplines.

There is a wide array of evidence that interdisciplinary work is becoming more important to successful innovation. For example, Fleming's study of 17,000 patents has shown that multidisciplinary teams generate patents with a wider spread of success rates than homogeneous teams: the number of failures is greater for multidisciplinary teams, but the most spectacular successes come from such teams as well.[395] This may in part be because interdisciplinary knowledge is required even to plumb the depths of one's own field. Surveys show that more than 60 percent of Ph.D. students drew on more than one discipline during their Ph.D. research. Interdisciplinary Connectors are critical to advancing innovation.

In Chapter 6, we saw that high schools in particular limit the development of STEM Deep Divers, in part by rigid breadth requirements. Here we tackle the problem that the Interdisciplinary Connectors are shortchanged by higher education's equally rigid depth requirements—particularly at the graduate level, where thesis, qualifying exams, and course selection are all encased in a single-department-driven set of constraints.

Certain externally imposed reward systems drive universities to maintain a "disciplinary culture" and stifle the production of interdisciplinary connectors. Federal research funding criteria and published rankings, in particular, reward individuals, departments, and institutions that do not stray far from established disciplines. These twin drivers of reputation and money ("fame and fortune") reinforce existing silos. We therefore suggest several changes to federal funding drivers, in the form of revised grant criteria, and to rankings lists, in the form of a new, industry-generated ranking system, which will reward institutions that engage in the diversity of ideas and training needed to excel in an innovation economy.

ARGUMENTS IN FAVOR OF INTERDISCIPLINARITY IN HIGHER EDUCATION

There are a number of arguments in favor of greater interdisciplinarity in STEM education. Perhaps the most important one is that the STEM work environment is inherently interdisciplinary. A number of high-profile science policy reports have argued that interdisciplinary education is sorely needed because the work environment is interdisciplinary/multidisciplinary, even if the academic system is not.[396]

While data on employers' need for interdisciplinary job skills are rare, what does exist show that employers value STEM workers with interdisciplinary education. For example, Professional Science Master's students with interdisciplinary "Applied Life Sciences" degrees graduate with salaried job offers of $60,000, compared to a national average of $40,000 for most master's-degreed students in the biological sciences.[397]

Another indicator is the nearly perfect 100 percent employment rate of graduates of NSF's highly selective interdisciplinary graduate program, IGERT (Integrative Graduate Education and Research Traineeship). As the name suggests, IGERT enrollees focus their graduate education on interdisciplinary connections. Moreover, 94 percent of the graduates believe it was the IGERT experience that gave them an edge in landing a job. Interestingly, the additional interdisciplinary training in the IGERT program came at no extra cost in student time-to-degree: IGERT students actually graduate on average six months earlier than their non-IGERT peers.[398]

Interdisciplinarity is also important because it brings with it the promise of expanding the STEM talent pool. Student demand for interdisciplinary training far exceeds the supply of such opportunities available. In one poll, more than 75 percent of students who were not in the IGERT program said they, too, were interested in interdisciplinary education when they applied to graduate school.[399] They just weren't able to access these opportunities, since enrollment in them was limited. Placing more interdisciplinary opportunities into the graduate curriculum would attract and concentrate those predisposed to interdisciplinary work. More interdisciplinary coursework would also filter out (via course grades) those who cannot succeed in it. Our current gating system is agnostic to this talent set and de facto screens out many of the individuals predisposed to excel in interdisciplinary work.

Women, for example, are underrepresented in STEM, even though they are preferentially attracted to interdisciplinary STEM work.

Women, for example, are underrepresented in STEM, even though they are preferentially attracted to interdisciplinary STEM work. The IGERT programs in the area of environmental systems (interdisciplinary work that crosses earth systems, ecosystem management, and environmental science and engineering) drew 57 percent to 80 percent female participation, even though the female representation in any one of the individual disciplines was no higher than 55 percent.[400] Olin college, which has a highly integrated interdisciplinary engineering program—and offers only engineering degrees—has a 44 percent female enrollment compared to a 22 percent representation rate for women in engineering nationwide, aggregated across individual field "silos." Professional Science Master's programs, which offer "more interdisciplinary training, often in informatics, computation or engineering, than a typical science degree,

Professor at the Massachusetts Institute of Technology in Boston, Massachusetts reviews a chemical solution with her peers.

have a 50 percent female participation rate.[401] A UK survey of researchers in higher education showed that female researchers spent more time on interdisciplinary research at almost every age (the largest gap was for researchers under 30, where females spent 20 percent more time on interdisciplinary research than their male peers).[402] It has been hypothesized that interdisciplinary work is highly attractive to underrepresented minorities as well, though we were not able to find data that either supported or refuted this claim.[403]

FEDERAL PROGRAMS DESIGNED TO EXPAND INTERDISCIPLINARITY

The above arguments for interdisciplinarity began to emerge in the mid-1990s. The 1995 National Academy of Sciences report, *Reshaping the Graduate Education of Scientists and Engineers* recommended greater "versatility" in the STEM educational experience, particularly at the graduate level.[404] In response, a number of new initiatives were established, including NSF's IGERT program.[405] In the program, faculty are invited to submit grant applications that allow them to create an interdisciplinary graduate training experience—a combination of courses, research and other activities, typically centered around a new interdisciplinary topic—for a small cadre of students at their institution. The grant dollars cover curriculum development and operation costs, including student stipends and tuition. Successful IGERT grants typically expose students to more than one field by insisting on out-of-field coursework, out-of-department research internships/coops, and project-based activities/research that engage multi-student teams drawn from disparate departments. The IGERT program was sufficiently successful that it inspired the creation of a similar program by the Canadian Government, CREATE.[406] Germany has also established a similar program, Research Training Groups.[407] However, IGERT is small in scale compared to the need: in its 12 years of existence, it has been able to reach only 5,000 Ph.D. students, compared to the roughly 240,000 Ph.D.s who have graduated in STEM over the same time period.[408]

The 1995 report also motivated the creation of NIH's program, "Training for a New Interdisciplinary Research Workforce."[409] This program redefined NIH's research assistantships and traineeships (graduate student support programs) so that professors receiving such students had to include some kind of interdisciplinary experience for them. However, NIH's explicit emphasis on interdisciplinarity faded after about two years.

The slow disappearance of the NIH program, compared to the success of the IGERT program, offers a cautionary lesson: interdisciplinary student training does not occur naturally in most university environments where professors are focused on targeted, narrow research that directly yields promotion, tenure and salary raises. Encouraging them to broaden the scholarly scientific experience of their students in this situation is, to say the least, a difficult sell. The IGERT program mitigates this problem by supplying an additional incentive for the professor (faculty salary costs can be charged to the IGERT grant, above and beyond their salary currently covered by research grants). In addition, the students on the interdisciplinary training are not necessarily those performing research for the professor. In contrast, the NIH program had no similar incentives or distinctions and as a result was not able to overcome the natural academic resistance to this type of structure.

This is not to say that there are no freestanding interdisciplinary STEM programs at colleges or universities. There are a number. As discussed above, Olin College does this, but it was explicitly designed around this approach. Duke University is piloting a doctoral program to train engineers that can work across fields to find solutions to global challenges. Likewise, the University of Delaware is building an Interdisciplinary Science and Engineering laboratory that will locate classrooms next to Institutes focused on energy, environment, and public policy. But while there is some growing interest in interdisciplinary learning, it is nowhere near as prevalent as it could be in part because of the divergence between faculty incentives and student interests.

The interdisciplinary government-industry fellowships proposed later in this report avoid this faculty conflict of interest by giving funds directly to the student, as is common with all fellowships. However, the principle of student control could theoretically be extended beyond fellowships, even to students on research assistantships (i.e., students supported on research grants to faculty). This could be accomplished by divorcing the student-support component of every research grant from the faculty-support component and giving the student portion directly to the student. Such a mechanism would free the 30 percent of our nation's graduate students on research assistantships to pursue their own interests, independent of faculty pressures to stay in-field and focus exclusively on the research project at hand.[410]

In this more flexible research assistantship scheme, faculty would apply for research grants as before, but grants would arrive at the university in two parts: a student support portion (tuition + stipend) that is awarded to a student and henceforth travels with the student; and a research support portion (professor salaries, equipment funds, materials, etc.) that stays with the professor. The fact that the student is now the master of his own destiny, and the professor must "court" students to work with him, should push faculty towards allowing students greater freedom in indulging their interdisciplinary passions. According to the NSF poll performed in conjunction with the IGERT program review, more interdisciplinarity was an option that 75 percent of students crave.[411]

We recommend these three options. However, we also acknowledge that the forces that keep universities entrenched in silos, and prevent students from becoming true "Interdisciplinary Connectors" are strong. Thus, we also recommend going further and dismantling the "system" that reinforces the siloed nature of university education.

INCENTIVES FOR HIGHER EDUCATION TO REMAIN IN SILOS

Above, we briefly allude to the fact that faculty are poorly motivated to cross disciplinary boundaries, particularly when it comes to the training of their own graduate students. As we discuss in the sections that follow, this siloed culture, so characteristic of academia, is set by an externally imposed reward system. The reward system includes money—specifically federal research funding—and reputation—specifically, public rankings of universities. Both favor activity within disciplines, as opposed to across disciplines.[412]

Federal Research Funding Rewards Field-Centric Professors and Departments

Federal research funding supplies a significant share of professors' salaries, graduate student stipends, and overhead/operating expenses for academic departments. Consequently, there is extremely strong survival pressure to obtain federal research grants, with the result being that whatever attracts these grants dictates what is "valued" in higher education. Deans and department heads, looking to make budgets meet, will be acutely aware of who is "pulling their weight" by securing research funding and who is not. The former are rewarded, the latter, left behind.

To understand why federal dollars have such a large influence over university decision-making, consider the sources of income for the University of Michigan. Student tuition is the primary source of funding, but government contracts and grants is the second largest. (Table 7.1) This pattern holds true across all public universities.[413]

Table 7.1: Revenue Sources for the University of Michigan, 2010[414]

Source of Revenue	Percent of Total
Student Tuition	37%
Government-Sponsored Research	29%*
State Appropriations	12%
Investment Income and Other	11%
Corporate & Privately Funded Research	11%*

Tenure and promotion are examples of internal rewards employed by department heads and deans that rely on measures of external research funding. Even when "dollars of research grants" is not explicitly required in tenure write-ups, "number of students produced," "numbers of publications" and "reputation" (letters of recommendation) are. In STEM fields, these are by and large proxies for research funding, because the number of students produced is set by the amount of funding one has to support them; the number of publications is set by the number of students employed producing them; and reputation is established in part through student-generated publications and conference presentations, all of which trace their roots, ultimately, to the size of the professors' funded-research portfolio.

To truly change the culture of higher education, and to encourage greater acceptance of interdisciplinary research and teaching, the rules surrounding federal grant awards need to be changed. At present, the federal grant award criteria and processes dominantly favor in-field research and researchers (despite the availability of specific grants that will fund interdisciplinary work). Specific field-reinforcing criteria are discussed below. Formal peer review at NSF, NIH, parts of USDA and DoE tends to include some or all of these criteria as specific line items in either the proposal submission forms or the ranking forms; less-formal program manager review (DoD) hews to the same principles but does not require explicit line itemization.

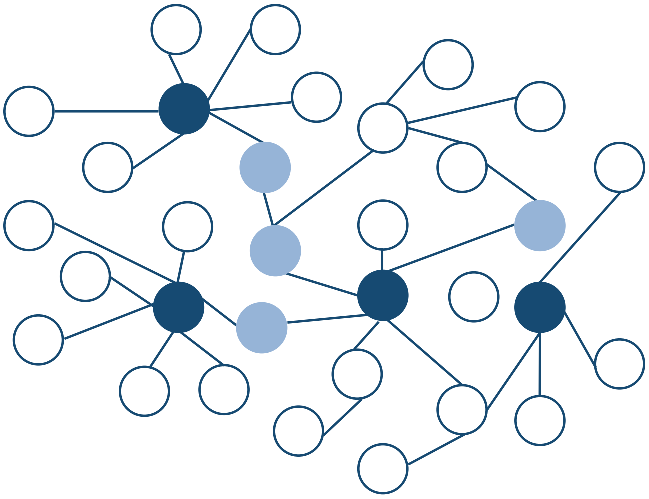
A number of proposal criteria reinforce disciplinary silos. One is the "number of publications" criterion, which rewards researchers who maintain a small army of Ph.D.s dedicated exclusively to academic publishing, in fields where established journals already exist. The "number of publications" criterion also rewards older, established researchers at the expense of younger ones, who have not yet had a lifetime to accumulate large numbers of publications. To its credit, NSF now asks grant seekers to list only their top five publications (and top five "related" publications).[415] However, after years of habit, researchers still tend to indicate the total number of publications on their submitted application or resume. Inclusion of these large numbers impresses reviewers, but they reflect length of time in-field far more than quality or utility.

A second field-reinforcing criterion is the reputation, track record, or "merit" of the researcher. Asking reviewers to "evaluate the researcher's track record" or "the merit of the researcher" is a thinly veiled popularity contest. Such a criterion requires the grant-seeker to be well established in a field where there are peers whose contributions fall into a "track" of known journals with longstanding reputations, or who have spent time in research labs with a history of illustrious advisors. More subtly, this criterion rewards researchers with tight social networks in one field, often at elite institutions within the field, because it is by virtue of repeated exposure to top-tier associates that reputations build.

Social network analysis underscores this point. From de Solla Price's 1965 analysis of scientific co-authorship to Wagner's 2010 analysis of nanotechnology collaboration at DOE centers, it has been repeatedly demonstrated that scientific collaboration networks follow a power-law distribution.[416] Power-law, or "scale-free," networks have a hub and spoke appearance, where individuals central to a field occupy hub positions, while their students/associates/collaborators lie at the ends of spokes. Each of the terminal points of a spoke may, in turn, be the hub of a smaller cluster—and so on. However, only a very few individuals occupy connector positions between large clusters, and they tend to be linked to only one or two individuals in each cluster to which they connect. These are our prized Interdisciplinary Connectors—the ones who link clusters of disciplinarity.

Reputation measures can easily identify the center of a hub, because many individuals are linked to that person and know of them. However, the geometry of social networks means connector individuals have far fewer social connections. They are rarely well known. For this reason, "hearsay" reputational measures should not be used to evaluate scientific grant applicants. Such measures reflect the centrality of a person to the hub of a social network (and by definition disciplinarity) and discriminate against researchers who connect disparate fields.

Figure 7.1: Schematic diagram of a hub and spoke network: hubs (in grey) are central to a field; interdisciplinary connectors (in blue) have fewer connections



A third field-reinforcing criterion is the identity of researcher and/or home institution. The process of peer reviewing federal grants uses single-blind review: the name of the author and institution is known to the reviewers, but the identity of the reviewers is not known to the author—an arrangement that encourages reviewers to be candid. A recent survey of the literature on single vs. double-blind reviewing indicates that very strong proposals or papers will not be hurt by exposing the name of the author and institution, regardless of origin; however, weaker proposals or papers will be viewed far more favorably if coming from an individual from the same institution type/gender/background as the reviewer. The net result is that, in proposals that may deserve funding but where judgment is required, weaker work is found acceptable when coupled with strong ties to the reviewing panel. This however crowds out work of stronger quality that comes from individuals or institutions having characteristics unlike the review panel. The bias in peer-review panels comes, not from reviewers dissimilar to the applicant—absolute ratings do not go down from dissimilar reviewers. Rather, they come from reviewers similar to the applicant. The latter individuals will tend to rank proposals from applicants with similar demographics, field, and institutions as themselves, more highly.[417]

When making difficult decisions, a peer review panel with first-tier research university (Research I) panelists (the norm) will therefore respond more positively to a Research I university affiliation on a proposal than to the name of a primarily undergraduate institution, a community college, a historically black college, etc. This bias crowds out institutions that are more industry-targeted (many community colleges or smaller state universities craft unique curricula or conduct research that is related to the needs of regional industry), more teaching-focused, (in the case of primarily undergraduate institutions) or whose structure and funding render them innovative in entirely new directions. For example, the high degree of rigor by which the costs and benefits of ecological sustainability is measured throughout the MBA curriculum at the Bainbridge Graduate Institute, or the unusually high access to global experts and analysis at Farleigh Dickinson University, are unique opportunities that provide fascinating research tools for scientists and non-scientists alike. However, institutions like these are not Research I universities and would suffer in a limited funding pool coupled with a pro-Research I bias.

Restructuring the Federal Research Grant Selection Processes

Extrapolating from the above discussion, interdisciplinary work would be rewarded more frequently if grant proposals were restructured in a number of different ways.

Instead of number of publications, impact criteria such as the citation frequency of the researchers' five top publications and patents (or perhaps even the use frequency of an invention, since not all inventions are publicly patented), should be used. If the grant applicant persists in adding the number of publications to his grant application, this biasing information should be redacted by program officers before the proposal is handed to review committees.

Because reputation is typically used as a proxy measure for the applicant's competence, we suggest that competence instead be deduced from the proposal itself: does the proposer evidence understanding of the problem to be tackled? Is the approach sound? Alternatively, one could ask for two or three letters of recommendation supporting the past accomplishments of the applicant. This would require only two to three social contacts. Both an interdisciplinary connector and someone who is central to a field should be able to deliver on this more limited requirement.

If there are concrete issues regarding the non-performance of the researcher on a prior grant, or lack of suitable equipment at the home institution, the program officer can and should take up these issues with the grantee, but separately from the peer review. Particularly as federal agencies move towards common reporting requirements on grants, and a common system for grant processing, non-compliant/non-performing researchers will become ever more visible.[418] The peer-review panel need no longer provide opinions regarding past performance if the facts themselves are readily available.

An alternative to exposing the identity of the researcher/home institution is double-blind reviewing, in which the reviewers do not know the author's identity and the author does not know the reviewers' identity. This is accomplished by having the program officer redact all identity information from the submitted proposal. While it is impossible to completely eliminate identity clues (many grant applicants tend to cite their own work so heavily as to make their identity obvious), double-blind review would at least diminish the favorable bias that exists between reviewers and proposals that come from "people like them" (in the same field, from the same type of institution, with similar demographics).

Finally, ideally, the composition of review panels for interdisciplinary grant applicants should match the applicant. However, composing a review panel purely of individuals conducting work in the same (tiny) cutting edge interdisciplinary field, from similar institutions, is painfully difficult to implement. How many "astro-biochemists" are there? Peer-matching to both a novel field and an unconventional institutional is nearly impossible.

Our solution for minimizing bias in peer review thus consists of minimizing the core of reviewers who are "exactly like the applicant" in review panels, and doing so uniformly across the board. This is in fact the opposite strategy from the current approach of taking a solid core of "usual suspects" and then diversifying it a bit with reviewers who are dissimilar to the core but similar to the (unusual) applicant.

To reduce the positive bias associated with the core, we recommend that all review panels contain a mix of academic specialties and institutions, but—and this is the key—no greater than a third of the review panel members should have both the same specialty and the same institution type as the grant applicant. With the biased core reduced to well under 50 percent, the final decision of the review panel should no longer reflect a preference for those in a field relative to those who straddle or move between fields. Furthermore, a broad committee composition forces grant applicants with narrow interests to be able to express, argue and articulate those interests to professionals who are non-experts. An ancillary benefit is that this practice would coach researchers in articulating the value of their research to those not in the field, i.e., to the public and to Congress.

In line with asking for review panels to include representation outside of a single academic discipline, agencies should include peer-review panel representation outside the academic sector as well, up to the one-third limit described above. Doing without industry input to the peer review process (as is the norm now) engenders a serious flaw in our national innovation competitiveness: we miss a feedback opportunity for directing student research and training towards the emerging challenges of our industry sector, many of which will be interdisciplinary in nature, and many of which are sufficiently relevant, that they make the many years of higher education more compelling to STEM students. Furthermore, industry is steeped in processes and concepts (e.g. design of experiments, lifecycle cost analysis, continuous quality improvement, systems analysis) that are foreign to many academics but major intellectual contributions in their own right.

Industry representation is needed on review panels for proposals submitted by individuals with strong industry ties (which includes the work of interdisciplinary connectors) to ensure they receive a fair chance at funding. While industrial participation in federal processes always raises suspicions over conflict of interest, this can be eased by seeking out newly retired industry workers or engaging in an active recruitment effort to attract other qualified individuals as described below.

One reason industry is not better represented on review panels is that recruiting industry reviewers is difficult. In the 1990s, when industry relocated many of its researchers from central corporate research laboratories out to individual business units, the cadre of industry scientists regularly attending academic conferences shrank. As this was the primary intersection point between corporate researchers and government agency program managers, it seemed corporate researchers had simply disappeared. However, corporate researchers do still exist, and therefore should be findable. We recommend that OSTP develop a plan by which federal agencies could easily locate corporate representatives for review panels, perhaps by organizing referral trees through prominent industry trade organizations (the Industrial Research Institute or Semiconductor Research Corporation, to name a few) and/or corporate research VPs or by working a booth at trade shows. The corporate reviewer recruiting plan should explicitly include a strategy for recruiting recently retired corporate researchers, who have more time to spend on extramural activities. It should also include a mechanism for giving visible credit to the industry participants so that what is lost to the company in employee time spent reviewing, is made up by increased corporate visibility and public good will, in line with the return on investment for other corporate citizenship efforts.

In addition to increasing the industry membership on grant review panels, federal agencies can encourage more interdisciplinary work by rewarding or requiring industry cost-sharing on the grants themselves. Federal agencies sometimes require universities to supply cost-sharing (also known as matching funds) as a grant requirement. We laud NSF's recent move away from having these funds be an ambiguous "factor" in peer review, to having the amount become a clearly stated, up-front requirement in the few cases where it is still mandated.[419] The elimination of voluntary, unspecified cost-sharing has prevented research grants from simply being awarded to the highest bidder in the equivalent of a sealed bid, silent auction. This in turn has prevented the consolidation and concentration of resources to the point where only a few dozen Research I institutions could compete.

Nevertheless, even when cost-sharing is required, it is still expected in many cases that the university itself will be the source of matching funds. In our view, this isolates the university from the broader economy and reinforces its own disciplinary culture to the exclusion of outside influences. A prime example is NSF's Engineering Research Centers (ERC), which currently require up to 20 percent cost-sharing, all to be borne by the university. The goal of the ERC program is nominally to "develop a new interdisciplinary culture in engineering research and education in partnership with industry to strengthen the competitiveness of U.S. industry." However, notwithstanding the lofty goals, no financial or other interaction with industry is actually required.[420] By encouraging industry funding, we will not only directly spur U.S. innovation and competitiveness, but will also reward those researchers willing to engage with new organizations, new influences, and new ideas. At the same time we will make STEM education more attractive for a wider range of students and provide them with an education that is more relevant to the needs of industry and the overall economy.

Cost-sharing is currently viewed as a means of shedding some of the financial burden of a grant onto a non-government partner. Viewed as such, it is logical that only large institutions, such as universities, should be asked to commit to this level of burden. However, cost-sharing could instead be used as a form of customer outreach and buy-in. If the cost-sharing requirement is set low enough, and if it is sourced to the perceived customers of the research, then cost-sharing can evolve to a form of community participation in the framing of the research. This then broadens the disciplines, views, and orientation of the research itself as well as rewarding the researchers capable of reaching beyond their laboratory door to outside partners.

We recommend that research with an innovation goal always have a cost-sharing requirement with industry, but that this requirement be low (e.g., $5,000–$30,000) as long as evidence of its industry origin can be supplied. This level of commitment is not a burden but does force the researchers to begin to engage and communicate with their industry colleagues prior to proposal submission—thereby broadening the viewpoints brought to bear on the research itself. Industry cost-sharing also ensures that industry has "bought into" the work enough to be a potential customer down the road. In a similar vein, we would argue that research whose ultimate customer is the K–12 school system should require token ($1,000–$30,000) contributions, either cash or in-kind, from K–12 schools that are not parties to the currently submitted grant. Grants whose customer is the public (e.g., grants for science museum exhibits or "fun math" websites) can be forced to have a token cost-sharing requirement from the public, and acquire valuable feedback from that sector, in the process. The web now provides excellent mechanisms for micro-donation fund-raising from the public. An example would be the $27,835 in micro-donations raised for a math textbook and related website entitled "Punk Mathematics" by math lecturer Tom Henderson of Oregon State University, using the micro-donations service kickstarter.com. An excerpt from his "pitch" reveals the richness of thought engendered by the requirement of reaching a broader audience:

> Punk Mathematics will be a series of mathematical stories. It is written for readers who are interested in having their minds expanded by the strange metaphors and implications of mathematics, even if they're not always on friendly terms with equations. Better living through probability; the fractal dimension of cities and cancers; using orders of magnitude to detect bullshit; free will and quantum economics; and the mathematics of cooperation in a networked world on the brink of a No Future collapse.[421]

Would an NSF or Department of Education-sponsored project intended for public consumption, actually be consumed by the public? One way to find out is to force projects to have their potential customers vote with their wallets.

Changing specific grant criteria from the "blindness" of the review, to the review panel composition, to requirements for matching funds fundamentally changes the gates in the grant approval pipeline to allow more interdisciplinary proposals pass through. It consequently rewards researchers engaged in such work, and allows them to pass through their own gates in the higher education system. There will be losers in this process, particularly weaker proposals from established researchers in Research I universities. However, nothing in the proposed alterations touches the merit of the proposed research. Proposals are still reviewed; quality is still assessed. Some of the proposed changes (industry, public, or school cost-sharing) speak to whether there is an audience for the outcomes of the research, when such audiences are presumed in the submitted proposal. However, most of the suggestions are designed to prevent reviewers from judging the perceived merits of proposed work by extrapolating from the researcher's history outside of the grant proposal. Opening up doors for unconventional actors, with high-quality proposals, to engage in academic, leading-edge research is surely a win for all concerned.

INSTITUTING CHANGE

In many ways there is no shortage of ideas on what changes are needed in higher education to spur more and better STEM graduates, including more interdisciplinary education. But while many, if not most, of these ideas are worth pursuing, few are being acted upon. We understand what could be done, but lack the institutional incentives that would lead more of these practices to be adopted. We discuss several of these incentives here.

In the case of grant criteria that reinforce disciplinary silos, we have suggested specific changes. A thorough review of existing practices would uncover even more ways to eliminate existing biases. We therefore recommend using a panel of outside industry and other non-academic experts to re-envision grant applications with the goal that researchers who work with students in interdisciplinary or industry-friendly work are not actively excluded from the grant recipient pool.

In addition to the financial rewards associated with federal research funding, a major driver for higher education is reputation. Institutional reputation is not only a reward in its own right; it also drives student enrollment, a major contributor to financial survival (as illustrated for one institution in Table 7.1, above). Department heads therefore strive to ensure that their departments and faculty are "on top" in reputational rankings; if they succeed, they are rewarded with more resources (faculty slots, teaching assistantships, startup packages for new faculty, etc.), from their college's dean and the university's administration. The university reward system therefore reinforces academic silos in part because the existing reputational rankings reward academic silos—or at least, do not reward interdisciplinarity.

Current Reputational Rankings Drive Institutions Away from Interdisciplinary Education

The two most prominent rankings for STEM departments and faculty are National Research Council (NRC)'s *Assessment of Research Doctoral Programs*, produced every 10–15 years, and the annual *U.S. News and World Report* ranking of colleges and universities.[422] The National Research Council rankings includes a number of factors that are derived from a poll taken of faculty. (Table 7.2) Bold face indicates those factors that are proxy indicators for the research funding received by the institution, which is weighted towards rewarding in-field faculty. That is not to say that interdisciplinary grants cannot be had, only that the institutions that succeed in the current system are those with strong disciplinary structures and ties. Bold-italicized factors are those that are not tied to research funding but are nevertheless antithetical to interdisciplinary activity (e.g., for students to obtain an academic position, they need to be affiliated with a specific field, one established enough to have its own department). Between the bolded and bold-italicized items, approximately 50 percent of an NRC ranking is constituted by factors that depend on having faculty in established fields.

Table 7.2: Factors and Weights for the National Research Council Ranking of Research-Doctorate Programs[423]

Factor	Weight%
Citations per Publication	31.1
Average number Ph.D.'s graduated per year	**16.1**
Publications per Faculty Member	**13.7**
Avg. Math GRE score of incoming students	9.6
Percent of Faculty with Grants	**9.0**
Percent of Students in Academic Positions	6.7
Percent of First Year Students with Full Support	**4.7**
Honorary Awards per Faculty Member	4.0
Number of Student Activities Offered	2.6
Percent of First Year Students with Portable Fellowships	2.4

These rankings reflect a largely inward and self-referential view of what is important. For example, the average math Graduate Record Exam (GRE) score of incoming students only measures the selectivity and perhaps preexisting reputation for quality of the institution. Likewise, the percent of students in academic positions reflects the view of many faculty that the only really worthwhile positions are ones in academia. Moreover, if there is doubt on the matter of whether peer value is attached to interdisciplinary work, or whether such work is rewarded by rankings, one need only look at the factors not included in the NRC rankings. Table 7.3 lists factors that faculty nationwide were asked to vote on, with respect to inclusion in the NRC ranking weights, but which did not make the cut.[424]

Table 7.3: Factors that received negative or zero coefficients as a result of NRC's faculty poll and therefore are not contributing to an institution's standing in the NRC rankings[425]

Factor
Percent Non-Asian Minority Students
Percent Non-Asian Minority Faculty
Percent Female Students
Percent Female Faculty
Percent International Students
Percent Completing Degree within 6 Years
Time to Degree Full-Time and Part Time
Percent *Interdisciplinary Faculty*
Student Work Space
Health Insurance

Bold items are those that scale positively as interdisciplinary programs are introduced. They don't cause interdisciplinarity, but they are correlated with it. Bold-italicized items are directly related to interdisciplinary work. Eight of the ten factors that were not chosen are positively correlated with interdisciplinary activity. It is important to also note that no explicit innovation metrics appear in the table, e.g., factors such as industry funding, numbers of patents, or numbers of startup companies that persisted more than three years. Interdisciplinarity measures did occur to the academic community, but were not counted. Innovation metrics never even occurred to the academic consensus generating the NRC rankings.

> **Innovation metrics never even occurred to the academic consensus generating the NRC rankings.**

In short, if we wish to reward interdisciplinarity (or innovation), and ensure that interdisciplinary colleges, universities, and programs have the reputation to attract their fair share of students, the ranking system put forth by the NRC is not the appropriate tool.

To its credit, the *U.S. News and World Report* rankings utilize two factors (shown as highlighted boxes in Table 7.4) that scale positively with increased interdisciplinarity. At the same time, there is the larger factor of "peer assessment," which would scale negatively, because faculty place zero value on interdisciplinarity itself but attach strong value to external grant funding in all its manifestations, which in turn correlates negatively with interdisciplinarity.

Given a 25 percent weighting to factors that scale positively with interdisciplinarity, and another 25 percent weighting to factors that scale somewhat negatively with interdisciplinarity, the *U.S. News and World Report* rankings appear to neither value nor devalue interdisciplinarity in any strong way. Again, if we wish to reward institutions for interdisciplinary education by driving students (and their tuition dollars) to them, we cannot use the *U.S. News and World Report* rankings for this purpose.

Table 7.4: Factors and Weights for the *U.S. News and World Report* Rankings of Colleges and Universities[426]

Factor	Weight%
Peer Assessment	25%
Retention [through Freshman Year (4%) and through Graduation (16%)]	20%
Quality and Accessibility of Faculty [Class Size (8%), Faculty Salary (7%), Faculty degrees (3%) and other (2%)]	20%
Student selectivity (15%)	15%
Average spending per student (10%)	10%
Alumni giving rate (5%)	5%
"Additional" (beyond what would be expected) graduation rate	5%

Establishing an Industry-Driven Ranking System Should Reward Institutions Engaged in Interdisciplinary Instruction and Research

Given the lack of a suitable rankings system by which to promote exemplary institutions engaged in interdisciplinary education, we recommend that a new industry-based ranking system be developed. These rankings would express the desirability of a department's graduates as potential employees. Specific factors that might be included in such a ranking include percent of graduates employed six months after graduation, fraction of graduates occupying advanced positions in industry five years after graduation, average time to full-employee proficiency, average quartile of employees job rating, graduates' performance on industry-wide certification exams, etc. The rankings might also include measures of student innovation: student-authored patents, student startup companies formed, etc. Separate lists could be compiled for "best departments" at both the graduate and undergraduate level.

An industry-led organization concerned with STEM workforce issues, such as the Industrial Research Institute or the Business-Higher Education Forum, should take on the task of generating the metrics and weights by which academic departments' students would be evaluated.

An industry-led organization concerned with STEM workforce issues, such as the Industrial Research Institute or the Business-Higher Education Forum, should take on the task of generating the metrics and weights by which academic departments' students would be evaluated. The data collection and analysis could then be performed by a neutral survey research company. To encourage the results to be seen as unbiased towards a particular company, the funding for this activity should be provided by a philanthropic foundation (e.g., Sloan, MacArthur, Keck, Kavli, Kauffman). Given the extent to which both parents and students look towards a degree as a "ticket to a job," an industry-ranked list of "best departments" should garner an avid following, particularly if publicized in a popular magazine, for example, *BusinessWeek* or *Newsweek*.

Inasmuch as a deeply interdisciplinary educational experience better prepares students to work in industry, an industry-generated rankings list should reward those interdisciplinary programs that excel in giving students meaningful depth in more than one field. These same interdisciplinary connectors will comprise some of our future innovators, who in turn, will create new industries. Such a ranking will also provide increased pressures on colleges and universities to produce high-quality STEM graduates, regardless of field, who can work effectively in industry. In this manner, an industry-generated ranking of universities should help to close the skill gaps between students' training and employer needs, thereby also reducing spot shortages in STEM fields, a topic undertaken in Chapter 11.

Olin College of Engineering, Needham, Massachusetts.

Create New Kinds of STEM Colleges and/or STEM Programs: the Case of STEM Education Done Right at Olin College

We have argued that the twin forces of federal research funding and reputational rankings (which in turn generate student tuition dollars) drive colleges and universities towards a field-centric mentality and a siloed educational experience for students. If this hypothesis is correct, then institutions that do not have these same drivers should be able to create interdisciplinary connectors—students with expertise in more than one field—far more easily. Such is the case at Olin College, which derives 80 percent of its operating revenue from a $400 million endowment. Federal research funding is not critically needed, as it is in most universities, and neither are tuition dollars: until 2009, all students received full tuition from the College (now they receive half-tuition), which is funded by the F. W. Olin Foundation.[427] Olin has no departments, and the student experience is exceptionally rich and integrated. The case of Olin suggests that such institutional innovation, as opposed to simple tinkering around the edges so common to most discuss of STEM reform at the undergraduate and graduate level, will be needed to move STEM education in the United States to the next level. The educational process at Olin is one we recommend emulating.

The Olin College Paradigm for Educating Engineering Innovators

Franklin W. Olin College of Engineering was chartered in 1997 to reform and improve undergraduate engineering education.[428] It is an independent, highly selective, entirely undergraduate, residential engineering institution designed to prepare students "to become exemplary engineering innovators who recognize needs, design solutions, and engage in creative enterprises for the good of the world."[429] Admitting approximately 85 students per year since 2002, Olin's first class graduated in 2006. Approximately 80 percent of Olin graduates go into engineering, science and technology fields; 25 percent of Olin graduates are involved in start-up entrepreneurial enterprises (either full time or part-time), with 10 percent starting their own enterprises.

Olin College was founded in response to calls for change in engineering education. By the 1990s, the engineering community felt engineering curricula were not up to the challenges of the 21st century. Given the increasingly global and collaborative nature of engineering solutions, government, corporate and accreditation representatives began urging the addition of teamwork, project-based learning, entrepreneurial thinking, and communication skills to engineering curricula, as well as a greater emphasis on social needs and human factors in engineering design.

How Olin is Different

Given this new environment, Olin's organizational and curricular designs differ from traditional engineering programs in several regards. First, while it offers ABET-accredited degrees in electrical and computer engineering, mechanical engineering and engineering (with specializations available in bioengineering, materials science, computer science and systems, as well as a self-designed specialization), Olin has no academic departments and no faculty tenure.

Second, Olin students are selected in two phases. They are first identified as academically qualified "Candidates" through review of their records, then invited to a "Candidates' Weekend", where they and their parents meet Olin faculty and students, and participate in a design project, individual interviews, and team exercises.[430] The weekends assure that the College and its accepted students are well matched. Olin recruits actively for a variety of talents, experiences and capabilities; creativity and multiple intelligences are highly valued.[431] After matriculation, student passions are exercised by a wide, interdisciplinary range of academic and social experiences comprising Olin's "Learning Continuum." Overall, 44 percent of Olin's all-engineering student body is female, compared to approximately 20 percent nationally for engineering. On average, 17 percent of Olin students are minorities (by way of comparison, the non-white populations of Massachusetts and the United States are 14.1 percent and 20.4 percent, respectively), and more than 95 percent are citizens or permanent residents of the United States.[432]

Third, the goal of an Olin education is to graduate engineering innovators who have original ideas, valuable insights, and the capabilities to realize their visions and make a positive difference. Curricula focus on interdisciplinary and integrated teaching, hands-on learning and research opportunities for students, an emphasis on communication skills, opportunities for students to work in teams, exposure to other cultures, and a better understanding of business and management practices. Olin's education encompasses three broad areas, which all students study and practice: engineering and science, business and entrepreneurship, and design and human behavior.


Student team at the Olin College of Engineering in Needham, Massachusetts

Curricular Design

Olin's curricula are heavily interdisciplinary and many student experiences involve working in teams. The curricula exemplify the Olin philosophy that an understanding of engineering's societal context is an essential aspect of an engineer's education: since engineers serve the public and must deliver their product to that public via the marketplace, this context is necessary to realize the opportunities presented by an engineering education and to inform a future engineer's choices. Some specific examples of such context-setting in the Olin curriculum include the required first-year course "Design Nature," in which student teams build computational and physical models mimicking the behavior of living things (e.g., insects, fish) and learn basic project management along the way. In "Modeling and Control of Compartment Systems," first-year students explore a range of problems and study the modern tools and techniques used by today's engineers to model, simulate and control real-world systems. "User-Oriented Collaborative Design" challenges student teams to study and address the needs of their selected user group through the design of a product proposal; the user perspective gained by students demonstrably enriches their experiences in subsequent courses. "Fundamentals of Business and Entrepreneurship," typically taken in the freshman year, instills knowledge of business principles as student teams form and run businesses with counsel from faculty representing the company's board of directors; business profits are contributed to charities chosen by students, providing a portion of Olin's emphasis on philanthropy and ethics. Figure 7.2 provides a schematic representation of how these four courses span the space of engineering; it distinguishes a traditional, narrow definition of engineering education from the broader definition used at Olin, which shows the interrelationships between engineering, business and society.

Figure 7.2: Olin College View of Engineering as a Discipline[433]

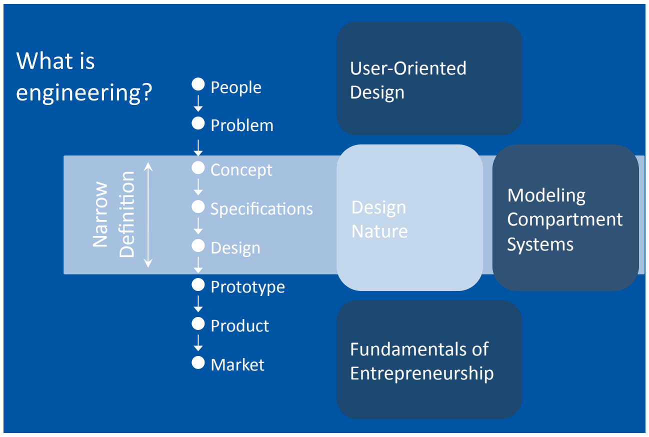
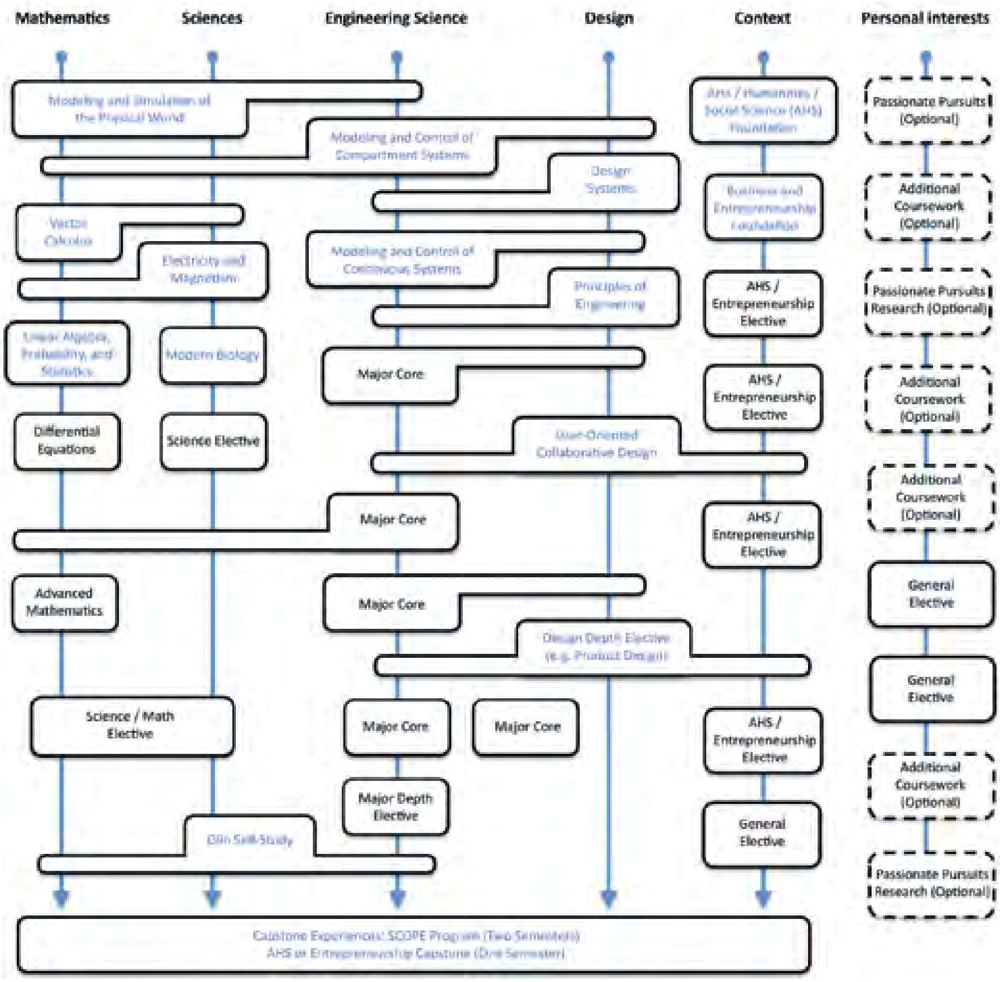


Figure 7.3 provides a schematic of the Olin curriculum, showing how courses span the topics of mathematics, science, engineering science, design and social/human context. Many Olin courses are interdisciplinary and several are co-taught by faculty from distinct disciplines. In Figure 7.3, "AHS" refers to arts, humanities and social science. Though each student will study both, individuals can choose to emphasize either AHS or entrepreneurship. Each student participates in a capstone course in either AHS or entrepreneurship. A second, yearlong engineering capstone in the senior year addresses an industry-sponsored problem relevant to their major field of study, and serves as a culmination of Olin's project-based education. The column labeled "Personal Interests" indicates subject matter that can be studied at the choice of the student and without credit. "Passionate Pursuits" and additional non-credit course material can fall into this category, which is faculty-monitored and noted on student transcripts. Olin students enjoy a relatively high participation in study-away experiences (approximately 25 percent) and in research internships (68 percent).

Student choice is an important aspect in much of the Olin curriculum, which includes elective courses throughout. In addition, students and student teams exercise choice on projects within courses, both required and elective. These choices allow students to shape projects to be reflective of their own particular passions and values. Choice is available within many courses and maintains high levels of student engagement and interest throughout the curriculum.

Figure 7.3: A Schematic of the Olin curriculum[434]



Curricular Effectiveness Metrics

The effectiveness of Olin's student-centered curriculum is evident in results from the National Survey on Student Engagement (NSSE), which assembles annual data from first- and senior-year students (FY and SR, respectively) attending hundreds of colleges and universities nationwide about their participation in "programs and activities that institutions provide for their learning and personal development."[435] Figures 7.4 and 7.5 show mean scores for Olin students, reported in standard deviations from the overall NSSE mean (shown as zeroes), as compared to averages for the NSSE sample of engineering programs and liberal arts programs, in five areas. Olin's "Active and Collaborative Learning" Benchmark Score is among the highest in the nation. The difference from other institutions or groups is particularly noteworthy for the first-year students. NSSE data, provided on a scale of 1–4 (poor-to-excellent), also show Olin's high ratings for: emphases on critical thinking (3.27 FY; 3.46 SR); solving complex real-world problems (3.71 FY; 3.53 SR); and synthesizing and organizing ideas, information or experiences into new more complex interpretations and relationships (3.61 FY; 3.67 SR).

Figure 7.4: NSSE Scores for Olin College: Freshman Year Student Engagement[438]

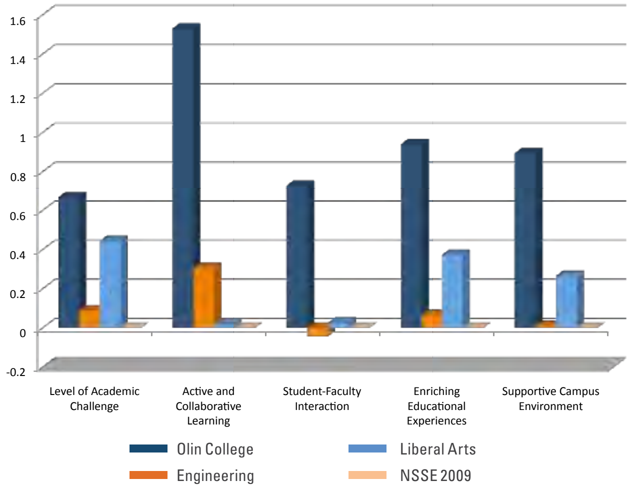
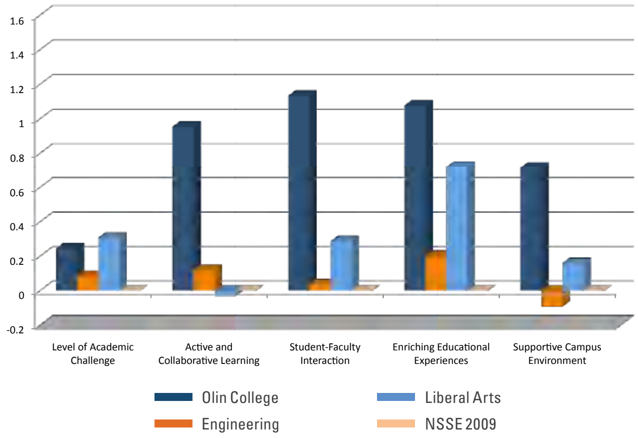


Figure 7.5: NSSE scores for Olin College: Senior Year Student Engagement[439]



Employers of Olin graduates also see them as exceptional. Surveyed at 24 months post-graduation, employers were asked to score their employees from Olin on a scale of 1–4 (poor-to-excellent). The results include: "making a positive difference in the profession," 3.74; "responding effectively to social, technological and global change," 3.57; "working effectively with a variety of different people," 3.67; "understanding the broad social, economic, ethical implications of his/her work," 3.44; "listening effectively," 3.68.

Perhaps most importantly, Olin students appear to enjoy their educational experience. Student surveys rank Olin as the nation's top engineering school.[436] Over 90 percent of those who enter Olin graduate, compared with a national college graduation rate in all fields (6 years after enrollment) of only 56 percent.[437]

Olin College is well suited to serve as an experimental environment for evaluating the effectiveness of a variety of curricular structures and pedagogical techniques. And the experiment appears to be a resounding success. But to provide sufficient "rocket fuel" for the American innovation system, we need more than the few hundred gallons of Olin fuel; we need hundreds of thousands of gallons of Olin-like fuel. This can mean creating more Olins—in other words, fostering more new start-up engineering colleges or creating Olin-like programs in existing engineering departments.

To test the broader applicability of Olin's novel approaches, the Olin-Illinois Partnership (OIP) was created in 2008 with the goal of exploring whether innovations pioneered in Olin's small, private engineering college setting can be scaled up to a large, public institution like the University of Illinois at Urbana-Champagne (UIUC), one of the world's engineering research powerhouses with over 6,000 undergraduate engineering students. (The OIP also joins the two institutions in a mutual effort to disseminate innovative pedagogical approaches and create a broad-based movement for change within engineering education).

In fall semester of 2009, UIUC provided approximately 80 first-year UIUC students the choice to participate in an experimental program called "iFoundry," designed to innovate improvements in UIUC's undergraduate engineering program and to adapt materials and techniques developed at Olin to the UIUC undergraduate engineering environment. Based on entering academic records, initial iFoundry students are typical of other UIUC students, yet after only one semester differences emerged. Those evaluating the experience of UIUC students report:

> Although we continue to assess and try to understand the Fall 2009 iCommunity experience more fully, preliminary results indicate that, not only did iFoundry students transition into college successfully as expected, they developed a strong voice, ambition, and identity toward their studies and the profession that is rare among incoming freshmen. Put another way, it appears that we may now be getting the Olin effect at UIUC in the iFoundry-iCommunity pilot.[440]

The spring semester 2010 has also had successful results, with Olin's "User-Oriented Collaborative Design" course offered at UIUC. The university will increase the size of the experimental group to 300 for the 2010–2011 academic year, making UIUC's population with experiences in this learning environment larger than Olin's. Plans are for the UIUC group to continue to grow.

Creating More Olin-Like Programs

The real question is how to scale up this kind of undergraduate education experience to many more colleges, departments and students. Olin's ability to improve engineering education is limited by its size, resources and vision. Its endowment determines the possible size of the school; proceeds from the endowment must support student tuition scholarships as well as institutional operating expenses. These requirements presently limit both the number of students Olin can serve and the extent to which the community can actively disseminate its lessons learned to other institutions. However, the elements of Olin's success can be expanded and adapted to other environments.

There are several possible paths forward. The first is to provide better information to students to create more demand for an Olin-like education. If there is a key to unlocking the passion for learning that energizes Olin's campus, it is found within a student-centered paradigm that presents learning challenges in an authentic, engaging way and also gives students the responsibility, choice and support to actively pursue knowledge and solutions to the increasingly complex problems of our global societies. As discussed in Chapter 5, increasing the availability of information on performance, including making mandatory the release of NSSE data and the creation of an industry-based evaluation system can create the kinds of "market demand" that will lead colleges and universities seeking more students and a better reputation to move in the direction of Olin.

In addition, funding programs directed at the departmental, college or school level appear necessary to accomplish the broad innovations in college experiences that will make students self-directed learners in their own educational experiences, rather than just dutiful respondents to classroom assignments. Ideally, funding programs should support increases in student engagement with interdisciplinary, team- and project-oriented engineering study, exposure to the empowering principles of entrepreneurship and design, and will relate the study of engineering to the needs of societies, unleashing students' passions for purposeful contributions.

Though grant programs designed to foster "institutional change" or "transformational change" exist (e.g., the "Transforming Institution" grants under the NSF Advance program), they are universally disappointing in terms of the amount of change they engender, compared to the dollars spent. For truly transformative change—in this case, to a more thoughtful, interactive, interdisciplinary model of education, we suggest the following guidelines:

1. The institutions receiving awards must meet certain performance benchmarks (e.g., improvements in NSSE scores) to continue to receive funding each year. This turns institutional change from a "nice to have" to a "must have" on the part of the principal investigators. The chosen performance benchmarks must be uniform across all submitted proposals—i.e., be a part of the funding announcement and criteria.

2. The transformation must be isolated from the broader context and culture of its parent institution, much as Saturn was isolated from GM. How the principal investigators plan to do this, should be outlined in the proposal.

3. The review panel for transformational change proposals should have no more than 30 percent representation from institutions of higher education, and that 30 percent should be comprised of individuals who have not only successfully implemented a significant institutional change of some kind in higher education, but have done so against impressive odds. In our view, a major reason why transformational change grants don't work is that the image of "change" is severely limited by the imagination of both reviewers and proposers. They are so deeply embedded in the system, they cannot think outside it. Forcing a different composition on the review committee at least eliminates the former problem.

CHAPTER 8:

Creating Entrepreneurial STEM Students

Student at the Massachusetts Institute of Technology in Boston, Massachusetts presents an experiment.

The first step in innovation is coming up with "the big idea." Our education system can facilitate this process by giving STEM students depth in their chosen field so they can push the frontiers of that field forward, into heretofore unexplored areas. In addition, the education system can equip our students to create bridges between two or more fields, thereby also forging settlements in uncharted territory. Whether they arrive at their new idea by being Deep Divers or Interdisciplinary Connectors, an idea is still just an idea. To transform it into an innovation, it needs to become a product or service with a market. Encouraging STEM higher education programs to focus more on entrepreneurship will not only help students become more entrepreneurial in their careers, it will also likely encourage more American young people to pursue and receive STEM degrees.

Thus, our education system also needs to equip Deep Divers and Interdisciplinary Connectors with entrepreneurial skills. Specifically, these students need to have the skills to take the idea in their heads a step beyond being described in a book or sitting on a shelf in a research laboratory. Whether their entrepreneurship is practiced inside or outside corporate walls, we need programs that help students take ideation to the next step, innovation.

HOW CAN THE EDUCATION SYSTEM PREPARE STEM STUDENTS TO TURN THEIR IDEAS INTO MARKET-RESPONSIVE PRODUCTS AND SERVICES?

The report, *The Anatomy of an Entrepreneur: Family Background and Motivation*, underscores the point that entrepreneurs are made, not born. Neither family wealth, nor personal predisposition ("wanting to be an entrepreneur since I was young"), nor having an entrepreneur in the family, are dominant factors in determining who ultimately becomes an entrepreneur. The typical technology entrepreneur is a middle-aged worker who never really thought about starting a company, but for whom the lure of building wealth and being his own boss finally takes hold, often via encouragement from friends and family.[441] The fact that entrepreneurs are made, not born, means we can influence their creation.

Very significantly, the one factor all entrepreneurs do have in common is a very solid education: most excelled in high school (over half saying they were in the top 10 percent of their high school class), and 92 percent went on to receive a bachelor's degree or higher).[442] Moreover, the education divide becomes even more apparent when looking at the success rate of companies produced: the 8 percent or so who started companies with only a high school degree produced companies that were more marginal: half as many employees and half as much revenue, on average, as companies established by those with B.S. degrees and higher.[443] Moreover, it's the learning itself and not the brand name of the school that matters: the 628 tech-company founders surveyed in *Education and Tech Entrepreneurship* represented 287 different academic institutions. Thus, providing youth with a solid education, wherever they are, is the first step in creating entrepreneurs. The steps outlined in previous chapters should help accomplish this. But what is it about the remainder of the education experience that generates so many more entrepreneurs out of MIT, for example, than neighboring institutions with much larger student bodies?

Engaging Students in "Real Design by Real Teams for Real Customers" is the Key

Entrepreneurship programs around the country are blossoming.[444] Entrepreneurship is popular in its own right, and courses are often established to attract new students or retain existing ones. While only 16 universities offered entrepreneurship classes in 1970, now over 2,000 do, at institutions ranging from private universities (e.g., Rochester Institute for Technology), to public universities (e.g., the University of Arizona), to community colleges (e.g., Wake Technical Community College in North Carolina).[445] However, many such programs are located in, or are affiliated with, business schools (e.g., Babson College) with the understanding that entrepreneurship is just one aspect of business.

STEM curricula need to contain "Real Design by Real Teams for Real Customers," if they wish to produce real entrepreneurs.

Deep Divers and Interdisciplinary Connectors need to have the skills to take the ideas in their heads and make them real, in a way that satisfies real markets. Tech entrepreneurship is a two-step process: first, the innovator must turn a mental concept into a tangible product (or service). Then the product must be brought to market (or the market to the product). While business schools teach how to bring a product to market, few business schools, even excellent ones, teach the preceding step, how to build a product from a mental concept. That is the function of engineering design, the other core element of tech entrepreneurship.

Engineering schools do teach design, as it is required for accreditation.[446] However the capstone design course often does not utilize multidisciplinary teams or market-driven requirements for the student design experience. It divorces design from market reality. Usually, engineering design in many engineering schools has objectives defined by a faculty member and executed by an all-engineering team of students. It comes perilously close to being an academically-defined undergraduate research project.[447] The idea becomes real, but not necessarily relevant.

In short, few business schools teach design. Few engineering schools teach market engagement. So, business majors lack engineering design, engineering majors lack market context, and science majors lack both. The solution is obvious: give students exposure to both engineering-design and market context by having them work together, in multidisciplinary teams, to create a tangible product against market-driven requirements. In other words, STEM curricula need to contain "Real Design by Real Teams for Real Customers," if they wish to produce real entrepreneurs.

At least two institutions stand out as exemplars of how to do tech entrepreneurship training right: MIT and Olin College. Nearly a quarter of MIT's students eventually become entrepreneurs.[448] Ten percent of Olin's student body haves already done so, even though Olin saw its first class graduate in 2006. Curves of company formation over time indicate that only 13 percent of companies launched by MIT alumni are launched in the first five years after graduation. Curves of company founder over time indicate that less than 4 percent of those who will eventually launch companies do so at an age of 23 or younger.[449] Extrapolating from these, we would expect the Olin number to increase to more than 50 percent or more of its graduates having started companies, once Olin has been in existence 30 years. This, in fact, is conservative; the projected numbers may be closer to 100 percent. Thus both programs generate extraordinarily high numbers of new company founders; the additional number of students who become intramural entrepreneurs (develop new marketable products while working within company walls) will never be known.

MIT and Olin colleges' entrepreneurship training contains elements that are found nearly everywhere: courses on entrepreneurship, business-plan competitions, and seminars. However, both Olin and MIT stand nearly alone in offering their students experience in creating a "real product," then moving it to market in a student multidisciplinary team where the product requirements were either defined by industry, or vetted by the marketplace, or both. At MIT the real product plus real market combination is accomplished through its mixed-team project classes, including "Entrepreneurship Laboratory," "Global Entrepreneurship Laboratory," and "Innovation Teams." (Table 8.1) At Olin, it is accomplished through its required user-oriented collaborative design class, its industry-defined capstone engineering project, and its capstone entrepreneurship project. We argue that it is the "Real Design by Real Teams for Real Customers," experience that is the key to MIT and Olin's success. Through them, students obtain hands-on experience in each step of the path from idea, to product, to market.

A recent analysis of MIT's entrepreneurial culture agrees:

> We believe the strongest impacts have derived from a cluster of project-oriented efforts … In these classes, the students organize in teams of four or five, preferably including participants from management and science, and engineering, to tackle real problems in real entrepreneurial organizations. Students select from the problems presented by companies that usually are quite young and in the Greater Boston area, although we have violated the distance constraint on many occasions. The intent is to work on "a problem that keeps the CEO up late at night!" With the emerging company CEO as the "client," the team devotes heavy time for the duration of a semester working on her or his issue, with class time spent on communicating general principles of team management, project analysis, client relationships, some commonly used tools of market research, and sharing progress reports with each other. The students learn much about teamwork and the issues facing early-stage, technology-based companies.[450]

Table 8.1: Entrepreneurship Activities at MIT[451]

Activity Title	Type
> 30 Lecture Classes Taught by Academics alongside Entrepreneurs and Venture Capitalists	Formal Coursework
Entrepreneurship & Innovation—a specialized MBA degree track	Formal Coursework
MIT Alumni Entrepreneurship Seminar Program	Lectures/Seminars/ Meetings/ Networking
MIT Enterprise Forum (globally televised panel discussions; local chapter meetings of VCs, CEO's, faculty students—anyone interested in startups)	Lectures/Seminars/ Meetings/ Networking
Topical Student Entrepreneurship Clubs (Astropreneurs Club, BioPharma Business Club, Energy Club, Mobile Media Club, NeuroTech Club, NanoTech Club, TinyTech Club, etc)	Lectures/Seminars/ Meetings/ Networking
Mixed Student-Faculty-Alumni Clubs that host occasional entrepreneurship field trips, lectures, etc (Sloan Entrepreneurs, Tech Link, MIT Innovation Club)	Lectures/Seminars/ Meetings/ Networking
National Entrepreneurship Conferences : MIT Venture Capital Conference & MIT Private Equity Conference (both organized & run by students), BioBash Venture, Cambridge (UK)—MIT Initiative Networking Conference	Lectures/Seminars/ Meetings/ Networking
Alumni Venture Clinics/Startup Clinics	Mentoring
Venture Mentoring Service	Mentoring
Adolf Monosson '48 Prize for Entrepreneurship Mentoring	Mentoring
MIT $100K Business Plan Competition	Business Plan Competition
Mixed Team Project Classes, including "Entrepreneurship Laboratory," "Global Entrepreneurship Laboratory," "Innovation Teams"(described further in the quotation below this table)	Student Projects
Seed Money (Research Commercialization Grants) for Faculty Company Launch (through the Deshpande Center)	Faculty Projects (often with Students)
MIT Industrial Liaison Program (companies pay a fee to have direct access to a pool of faculty consultants; faculty receive payments when they consult)	Incentives for Faculty Collaboration with Industry
Faculty Consulting to Industry Authorized at 1 day per Week	Incentives for Faculty Collaboration with Industry
Licensing of New Startups in Exchange for Stock in the Startup (i.e., licensing at little up-front cost to the startup founder)	Incentives for Faculty/Student Formation of Startups
Entrepreneur-in-Residence	Expert-in-Residence

It is important to note that MIT's "mixed team project classes" do not always include the actual product design; often, the design activity precedes the class, or may have occurred off-campus, in a company. However, the project is always centered around a real product (or service), engineering design is pervasive in the curriculum before and after the project, and the product's designer is generally a part of the team that is tackling the problem of how to get the product to meet its market. At both Olin and MIT, the student is actively engaged in each step of the path from Idea, to Product, to Market. The gap between the engineering school (Idea<=>Product) and business school (Product<=>Market) no longer exists.

While MIT and Olin are exemplary in their efforts to engage STEM students in entrepreneurships, some other universities are also active. Rochester Institute of Technology has created a special dorm for students who are or want to be entrepreneurs, and has located a design and prototyping lab right next door, which is open 24 hours a day so students can easily build and test their ideas. Likewise, UC Berkeley's Lester Center for Entrepreneurship and Innovation partners with universities and corporations worldwide to help students develop and bring new technologies to the market. For example, the Intel-Berkeley Technology Entrepreneurship Challenge showcases business plans that make use of novel technologies and have the potential to positively impact society through commercialization.

INCENTIVIZING UNIVERSITIES TO PROVIDE MORE EXPERIENCES THAT TRAVERSE THE IDEA TO PRODUCT TO MARKET CONTINUUM

The assumption that "Real Design by Real Teams for Real Customers" will be offered by all universities is inherently optimistic, since most do not offer it today. Nor do most offer industry co-ops, internships, or summer jobs, which can yield the same experiences offsite. The question is how can we incentivize universities to deliver these experiences?

Some solutions proposed elsewhere in this report, also apply to this problem: divorcing federal agency student support from research support (Chapter 7) allows students to engage in coursework they are drawn to, but that don't necessarily further the faculty research agenda—coursework like "New Product Design and Marketing." Ranking universities according to the quality of their students, as perceived by industry (Chapter 7) will reward universities that give their students experiences that prepare them for industry, or engage them with industry, which in turn gives them more "real product" and "real market" experiences. Removing incentives for faculty to remain in disciplinary silos (Chapter 7) also frees their students to pursue courses and experiences beyond the strict confines of the discipline. Creating joint government-industry fellowships (Chapter 10) gives at least these selected students some exposure to industry thinking and practice. Removing incentives for faculty to remain in disciplinary silos

But there are other bolder ideas that need to be adopted if we are to make real progress in this direction. Government should incentivize universities to engage graduate students more systematically with industry by driving university faculty into at least some industry-generated research projects. All too often faculty do not engage with industry and industrial research, and the result is less interdisciplinarity, less relevance of work to the students, less ability to create students with tech entrepreneurial skills, and less innovation and income for the U.S. economy.

Industry-university research centers appear to do a better job of educating STEM graduate students, in part by providing them with more real-world research opportunities. As one study concluded:

> There is emerging evidence that suggests industry-academia collaborations offer positive opportunities to students that are strong predictors of doctoral retention, including guaranteed funding throughout the doctoral program, networking opportunities for future employment, and social and academic involvement.[452]

A study of the effect of the NSF's Industry University Cooperative Research Centers (I/UCRCs) on graduate student training found that "Multidisciplinary center experiences was also a significant predictor for satisfaction and organizational commitment and was the largest predictor for perceived advanced technical and problem solving skills. These results imply multiple benefits may occur for the student if their center offers experiences that are 'hands on' or that integrate multiple academic disciplines."[453] The study went on to find that, "The more students interacted with industry members the more likely they were to be satisfied in their center and the more likely they were to report perceived proficiency in soft skills." Students that received funding from the center were fifty percent more likely to get a job in industry (as opposed to academia) than students that did not receive funding.[454] Industry-sponsored research centers may also do a better job of supporting female researchers (and perhaps by extension female graduate students). One study of I/UCRCs found that these "centers may constitute an institutional context in which some aspects of gender equity in science may be achieved."[455] Moreover, interaction with industry as a STEM graduate student is associated with significantly greater likelihood of producing intellectual property (e.g., patent, invention disclosure, etc).[456]

All too often faculty do not engage with industry and industrial research, and the result is less interdisciplinarity, less relevance of work to the students, less ability to create students with tech entrepreneurial skills, and less innovation and income for the U.S. economy.

The federal government incentivizes these relationships by requiring industry co-funding of academic centers supporting graduate research and faculty. NSF's I/UCRC program, which requires 4.3 to 1 industry: government funding, is a model. In the I/UCRCs, graduate research projects are often chosen by a vote of the center's industry members, and each project so selected typically has an industry mentor alongside the faculty advisor. Not only is the research itself more product and team-oriented, but these same industry members become close enough to the university faculty that they are then available to define and/or lead undergraduate design projects as well. Thus "Real Design, by Real Teams, for Real Customers" becomes accessible to both graduate and undergraduate students.

The result of such a partnership model is an increased rate of spin-offs. The NSF I/UCRC program, while it does not track the startups it has generated, is clearly creating more than one spinoff per year, because this is the rate of startup formation out of Berkeley's Sensor and Actuator Center alone since its founding as an I/UCRC in 1986.[457] The I/UCRC program currently supports approximately 40 centers like the Berkeley center, but its overall budget is tiny ($5 million to $7 million per year), largely because for NSF, Congress, and the academic community as a whole, these kinds of industry-university partnership models are at best an afterthought and at worst an attack on the ivory tower model of STEM education.[458]

As a point of comparison, NSF's Engineering Research Centers (ERC's) are larger centers that also purport to be industry-oriented. Across 15 centers, and with a budget that has historically averaged about $40 million per year the ERC program has generated 500 patents and 113 startups over 20 years.[459] A comparison of startup generated funding received shows the I/UCRCs are producing a minimum of 1.04 spinoffs per year, or 0.17 spinoff/startups per year per million dollars, while the ERCs are producing 5.65 spinoffs/year, or 0.14 spinoff/startups per year per million dollars. While the causes of the ERCs more limited performance may be multifaceted, one factor likely plays a key role. While I/UCRCs require industry co-funding, the ERCs—remarkably—do not.[460] The ability of I/UCRCs to reach more students (40 centers vs. the ERCs 15) sways the argument well in favor of the I/UCRC model, as a means of bringing students in contact with an industry-enriched, product-oriented experience.

To move universities in this direction, Congress should begin by expanding the I/UCRC program: a quintupling of NSF's I/UCRC program would cost only $23M additional dollars but allow it to reach 120 universities. They could do this by reauthorizing the American Competes Act in a way that would be budget-neutral within the Act. In addition, Congress or the NSF should require the ERCs to receive at least a portion of their funding from industry if they want to continue to receive NSF funding. That share could start at modest levels and ramp up over a number of years to at least a 1 to 1 ratio between industry and university funding. NIH should examine the NSF's I/UCRC model and propose an equivalent program to Congress. In addition, most current academic research centers funded from anywhere in the federal government should be examined for conversion to an industry cost-shared model. Not all centers are well suited for this purpose, but Congress can ask GAO to identify which of the federal agency programs that fund academic research centers have over $2 billion in extramural research funding. From this list, each agency can then be asked to choose programs totaling no less than $100 million a year to frame or reframe as industry cost-shared centers at a level of 20 percent or more. While it will be seen as an annoyance by many academic researchers to be required to reach out to industry for support, it is precisely this outreach we wish to incentivize, both to improve the quality of STEM post-secondary education and to boost U.S. innovation and competitiveness more directly.

Because an I/UCRC-type model can generate many startups, and give industry exposure to students, we suggest that incentives be created to push federally-funded university centers further towards this direction: renewal of industry-oriented centers, industry-cost-shared centers, and those claiming "innovation" should be predicated on metrics such as such as the number of university startup companies that have more than 10 employees after three years, amount of industry co-funding, high job placement rates of graduates funded by the center, and other criteria that reflect students' ability to subsequently move into the "innovation sector." A key output of these centers is not just the research itself, but the students who have the skill set to innovate at an advanced level.

One argument that some defenders of the current academic system make against industry-university partnerships like the I/UCRC model is that such partnerships limit academic freedom, particularly of the graduate students doing research. However, this does not appear to be the case. One study that used a stratified sample of graduate students from the same two engineering departments at six U.S. universities found that "the results failed to support claims that sponsorship by industry negatively affects student experiences or outcomes," and that there was no statistically significant difference in levels of academic freedom between industry-sponsored research projects and others.[461]

HOW CAN THE EDUCATION SYSTEM BETTER MOVE OUR STUDENTS' INNOVATIONS INTO THE MARKETPLACE?

Through immersion in "Real Design by Real Teams for Real Customers,"—the entire process line from ideation, to tangible product, to market insertion—students obtain the underpinnings for a future entrepreneurial career. But we can do more. A careful analysis of how entrepreneurs are "made" suggests we can dramatically compress the timeline for that "future entrepreneurial career" and move it into the present. At least some STEM students can be startup CEO's today.

The Big Three Barriers to Tech Entrepreneurship

A recent poll of 549 tech-company founders asked them what the dominant barriers were that "prevent others from starting their own businesses."[462] The top three factors cited were:

- Willingness to take risks
  (specifically, personal financial risks)
- Access to capital
- Business acumen

The education system is in a position to help students overcome all three barriers while still in school. The other significant factor identified in the poll was the time and effort required to start a company, cited by 93 percent of tech-company founders. However, most diligent students are willing to work hard.

At present, the "typical" tech entrepreneur deals with these the "Big Three" barriers long after leaving school via the following strategies:

- Personal Financial Risk; the tech entrepreneur waits to amass enough savings before quitting a job (tech entrepreneurs are dominantly middle-aged).[463]

- Access to Capital; the tech entrepreneur uses personal savings to finance company startup (tech entrepreneurs are dominantly self-financed).

- Business acumen; the tech entrepreneur works in another company long enough to understand "how business works" (75 percent of tech entrepreneurs had previously worked for a company more than six years—48 percent more than 10 years, before launching their own).[464]

The reality of having to surmount the Big Three barriers on one's own time and dime means most that entrepreneurs must graduate first, then spend a substantial portion of their lives in "real jobs" before beginning to launch their company.[465] It appears that it is the second barrier, access to capital, that is responsible for the length of the wait. Software companies, with their lower capital requirements, are launched by individuals at a much earlier point in their lives compared to other types of companies.[466] The age of an average software company founder is closer to that of a Ph.D. or post-doctoral student. Thus, if one could develop a mechanism by which to overcome all three barriers—particularly access to capital—while STEM students are still in graduate school, we could seamlessly tie the end of academic training to the beginning of an entrepreneurial career. To accomplish this, we envision establishing interlinked set of programs that directly addresses each of the Big Three barriers.

A Slight Realignment of Government and University Processes Gives Student Entrepreneurs the Ability to Overcome the "Big Three" Barriers

A number of steps could be taken to help STEM students be more entrepreneurial. To eliminate personal financial risk for students wishing to start companies, we propose an "entrepreneurial leave" mechanism be established. University and federal agency policies should be rewritten to allow capable STEM students to step out of their studies and research for a year or two to launch a company, and come back to their student lives if the company fails. Such a mechanism would take the personal risk out of company formation by providing a safe fallback.

While entrepreneurial leave is not needed for students who can simply quit school and live at home with wealthy parents during the company formation years, it is critical for scholarship students from poor communities and for foreign Ph.D. students and post-docs. For foreign students, "quitting school to form a company" is a recipe for deportation. Student visas last only five months after full-time enrollment ceases. Thus, both kinds of individuals need to have full-time student status during their leave year(s) as well as have a secure full-time student position to come back to.

We recommend the entrepreneurial leave option be available to foreign graduate students for several reasons. First, the percentage of foreign graduate students in STEM is large, at about 50 percent of STEM graduate students. Second, about two-thirds of these individuals will ultimately stay and work in the United States in any event.[467] Third, immigrants are associated with a higher rate of new company formation than U.S. citizens (for example, about 30 percent of the foreign students who attend MIT founded companies at some point in their lives, compared to 23.5 percent of the domestic students).[468] Finally, the entrepreneurial leave option gives a viable exit strategy for foreign students otherwise trapped in endlessly chained post-doctoral positions: if their company is successful, these students can obtain permanent residency via either the EB-5 visa or the currently proposed start-up visa.[469]

Implementation of an "entrepreneurial leave" program would require that federal agencies institute an automatic one-to-two year, no-cost extension on research grants (and fellowships) that support students who successfully petition for "entrepreneurial leave." The funding is reserved over that period and available again when and if the student returns to full-time graduate research. Universities would simultaneously have to be prepared to offer academic credit for the entrepreneurial leave period, in order to maintain the graduate student's full time enrollment status. The student never technically leaves the university, rather enrolls in a flexible number (up to some maximum) of "entrepreneurial study" credits, similar to the "independent research" or "independent study" credits given to graduate students engaged in full-time research. The entrepreneurial activity would be monitored by a faculty advisor who would assign a grade at the end of each semester (as in the case of research credits, these grades would reflect activity more than performance). Tuition payments from the student to the university are still required in this model, but would come from the student's startup company funding.

The federal government could then help overcome the access-to-capital barrier by enabling the Small Business Innovation Research program (SBIR) to fund graduate/post-doctoral students' startup companies. The SBIR program was established to bring the benefits of research and development to small companies.[470] It does so by giving small (<$100,000) grants for exploratory research, and larger (<$1M) grants for pre-commercialization development to small companies. At a time when seed money for new companies is virtually non-existent, the SBIR program is an island of resources for the transition of ideas to products. The SBIR program is also a natural bridge between the nation's research universities and small companies, because it is administered by the same federal agencies that give universities their research support.[471]

The SBIR program, modified slightly, could provide the source of capital to student startups, much as it does now for faculty startups. Because a bachelor's degree appears to be a minimum for successful company formation, our recommendations for student access to SBIR grants are limited to graduate students and post-docs. The agency supporting the largest number of foreign graduate and post doctoral students is NIH, at over 18,000 foreign post-doctoral students and 17,000 foreign graduate students.[472] Happily, NIH also has the largest pool of SBIR funding. Thus, opening up company formation to foreign students pursuing advanced degree studies in the United States puts the money squarely where it can do the most good: in the hands of the worlds' best and brightest technical minds, people who demonstrated by coming here that they are not afraid to take risks, and who as a group have a track record of creating new businesses that then create jobs for U.S. citizens.

SBIR phase I grants are already designed to take companies from the "idea" phase to the "first prototype" phase, with $100K/six months funding, on average. The SBIR grant can therefore cover student salary support, tuition, and the material needs of the new company (if not too large) during launch. However, for this vehicle to work for student-run companies, Congress will need to alter SBIR guidelines to:

- Make individuals who are currently full-time graduate or post-doctoral students explicitly eligible for such awards, even if they are foreign nationals, as long as their business is located in the United States.

- Make tuition payments an explicitly allowable expense under the SBIR guidelines, if the student is on official entrepreneurial leave (this then enables students on entrepreneurial leave to maintain full-time enrollment with their university via the mechanism described above).

- Create a special exemption for students, such that companies need not be in existence when the grant is being applied for. Instead, the student-run company could be created after the "intent to award" is received—or anytime before the actual award of funds.

- Encourage, via committee report language, the time period of Phase I awards to be extended for students, to up to two full years. This allows an "entrepreneurial leave" year to synchronize with an academic year, and also allows foreign students time to generate enough U.S. jobs and revenue via their company to obtain permanent residency via either the EB-5 visa or the currently proposed start-up visa.[473] The total award amount would remain at the current level of approximately $100,000/grant; for students, the grants would simply run longer than their usual six month duration.

- Ensure that students who successfully complete an SBIR Phase I project are then eligible for SBIR Phase II funding, under the same policy.

In addition, Congress will need to work with the Department of Homeland Security to:

- Ensure that students who receive SBIR funding (and derive their salaries from that funding) are still defined as full-time students while on official "entrepreneurial leave," and not as company employees, for visa purposes.

These changes are minor tweaks to existing SBIR legislation.[474] They create an additional category of applicant for the SBIR awards, but they do not change the size of the awards, or the process or criteria that govern agencies' selection of awardees.

Because business acumen is so critical to successful company launch, we recommend that student SBIR recipients have a strong management team in place that includes at least one experienced entrepreneur. This should be a requirement for all SBIR ventures, but is more critical for less experienced applicants. The SBIR application should also require the student to demonstrate prior experience in "Real Design by Real Teams for Real Customers," because this is such a formative experience for young entrepreneurs. Making this experience a program requirement will pressure universities to make such offerings available to graduate students.

CHAPTER 9:

Expanding STEM Graduates

Previous chapters have focused in large part on improving the quality of STEM graduates, but these efforts will simultaneously increase the demand for STEM workers by helping to spur innovation in the U.S. economy. Moreover, as discussed in Chapter 3, in the future the United States may not be able to rely on foreign STEM talent to power our innovation economy in the future. For both of these reasons, we need to focus specifically on expanding the number of American permanent residents who have STEM degrees.

While current STEM policy on expanding STEM workers focuses almost entirely on the K–12 level, we believe that changes at the college level hold significant promise. Increases of 20 percent to 30 percent are needed to meet the Bureau of Labor Statistics 10-year projection for S&E employment growth for 2016. Especially in the short term, this growth can best be achieved through a subtle redesign of higher education.[475] Higher education is not only closer to the point of job entry, it is also arguably less difficult to redesign than K–12. Even significantly reducing the 36 percent STEM dropout/switch out during college would yield the necessary numbers.[476] Yet, as currently structured, it appears that higher education could be doing much more to address this challenge. As Romer notes in a study of STEM education, "The picture that emerges from this evidence is one dominated by undergraduate institutions that are a critical bottleneck in the training of scientists and engineers, and by graduate schools that produce people trained only for employment in academic institutions as a side effect of the production of basic research results."[477]

Significantly increasing demand for STEM workers would necessitate going back further into the pipeline to redesign K–12 education. Such a K–12 strategy is already needed in certain fields, such as computer science (as distinct from routine programming) for which industry requires major influxes of personnel on a continuing basis. The IT sector is already one of the largest hiring forces in STEM, employing approximately three million graduates (40 percent of all STEM occupations), and one that remains at the forefront of global technology growth patterns.[478] Strategies for increased production of K–12 (high school), B.S., M.S. and Ph.D. students are discussed below.

HOW CAN WE PRODUCE MORE STEM HIGH SCHOOL STUDENTS?

There are a number of strategies that can be employed to produce more STEM high school students in addition to the strategies discussed in Chapter 5. A key strategy is to move to a college recruiting model.

National Recruiting from High Schools: If the NCAA Can Do It, So Can STEM

Our current approach to aquiring STEM talent from the K–12 system is to expose students to content, and then wait to see who shows up to apply for STEM department openings or, years later, jobs. This is a haphazard way of increasing our talent pool. Any organization seeking top talent—whether a C-level executive or a star athlete—uses a recruiting model, not a self-identification model. Does STEM deserve less?

Self-identification/self-promotion is a STEM career path filled with disastrous detours, potholes, and wrong turns. Students decide, with parental or peer or teacher input, that they are "good at math/science" or "interested in math/science" or not, depending on multiple random factors, many of which have nothing to do with raw talent: family expectations, an "inspiring" teacher (or not), a fun museum outing, societal stereotypes, or the fact that science is always a morning class. Students who commit to the next level of STEM education, for whatever reason, then structure their advancement using advice and influences from the same sources. This leaves course selection and career development to something slightly better than random chance, even for our most talented children—especially if they are bereft of social networks capable of delivering sound career advice. Moreover, students interested in one aspect of STEM (e.g., theory of math) often do not know if they "have what it takes" to attend a STEM-focused college and often opt to attend a more general university or liberal arts college. They may end up dabbling in STEM but majoring in something else.

Rather than letting random fate or personal intuition determine the future of our STEM workforce, the STEM community should instead develop a rigorous talent identification and recruiting program.

Rather than letting random fate or personal intuition determine the future of our STEM workforce, the STEM community should instead develop a rigorous talent identification and recruiting program. For example, rather than just waiting to see "who shows up" in the summer camp applications (effectively limiting enrichment opportunities to those already in the know, rather than those most talented), a researcher/outreach coordinator should visit local high schools, talk to high school teachers, observe students in the classroom, and obtain names of promising STEM students to recruit to the camps. Without this step, it is unlikely the pool of "identified" talent will ever be nearly as large or diverse as the pool of actual talent.

Teachers at every step of the way can be targeted by recruiters and asked to identify their most promising STEM students. Every outreach activity would be tied to recruiting at the next level. Summer camps that take in middle schoolers can act as a recruiting ground for a significantly expanded number of STEM high schools. High school students, either inside or outside of STEM high schools, would be recruited to after-school clubs, summer camps, and the like, where those with high interest would be flagged by the activity director, handed off to a college recruiter, and then given all the support he or she needs to make it to the college level. In this manner, all outreach activities—summer camps, invite-a-lecturer, afterschool activities, videogames targeted to youth—anything designed to "engage" students in STEM—can be used to recruit interested and talented individuals, and, via the outreach coordinators, enable an explicit handoff from one stage of student career development to the next.

In other words, the STEM community should model the recruiting practices of NCAA basketball, which does a superb job of identifying promising athletes from all walks of life by sending out recruiters to ensure those students make the transition from being the star on their high school basketball team to getting a college scholarship. Given the large amount of money made by professional basketball players, one would think that the "market" would work well in ensuring that the talent pipeline from middle-school athlete to high-school sports star to NCAA college athlete to the NBA works. In fact, it doesn't, and it is made much more effective by active recruiting.

A K–12 talent identification and hand-off model can work in STEM thanks to the large number of K–12 outreach activities already being funded by NSF, NASA and other federal agencies. An army of potential recruiters is already in place. To give some idea of the scope of existing outreach activities, a few such programs are highlighted in Table 9.1. In addition, every NSF research proposal currently requires an outreach plan under its proposal evaluation Criterion #2, which asks, "What are the broader impacts of the proposed activity?" The target of the outreach can be the general public, international audiences, the press, or undergraduates in other fields or other institutions. However, a significant fraction of the outreach that researchers propose is targeted to K–12. Typical activities include teacher development workshops in specific science topics, science summer camps for kids, hands-on after school activities in a science club run by the researchers, K–12 field trips to the researchers' laboratory, development of museum exhibits (the largest audience for these is K–12 school groups), mentoring programs for K–12 students, and special high-school science classes developed by the university for local K–12 students to enroll in (typically via partnership with a local school). Others are "invited lecture" series (researchers visit classrooms to give inspiring lectures), interactive web outreach (chat with a scientist online, run an experiment remotely online), working with high school teachers to develop a new curriculum, inviting K–12 students to professional society meetings and holding contests for them there (fuel cell car racing). The list goes on. Each of these activities brings K–12 students into contact with a researcher and/or grant-paid outreach coordinator. We merely need to transition these paid "emissaries of science" from being "content-out" delivery vehicles to being "people-in" recruiting vehicles.

Only a few changes need occur for current outreach activities to take on recruitment as a primary mission, thereby reaching much more aggressively into schools, similar to the NCAA model. Federal agencies, such as those listed in Table 9.1, would initiate the change to a recruitment-driven model by enforcing a set of reporting requirements on their grantees. In their formal funding announcements, including their Broad Agency Announcements, federal agencies would specify that any program designed to involve or partner with K–12 students or institutions will report on the efficacy of the recruiting effort used therein. Specifically:

1. Principal investigators (PIs) would be asked to list individual high school students (by name) they have identified as "STEM-interested" prior to the funded outreach activity. This list of names would arise from discussions between local outreach coordinators and high school teachers, as well as direct classroom observations of promising students by the outreach coordinator.

2. PIs would indicate what percentage of those students whom they targeted actually partook of the outreach activity.

3. PIs would identify the students (and/or families and teachers) with whom they had follow-up recruiting discussions after the outreach activity. These recruiting discussions would revolve around the next level of the student's STEM career. For example, an outreach coordinator responsible for a high-school student activity would follow up with a percentage of the participants and their families, separately or together, to answer questions they might have about college, high school course choice, how to fill out financial aid forms, and other steps of the high school-to-college transition.

4. PIs would document which of the students who attended the outreach activity were "handed off" to an individual at the next level of recruiting, and who that individual was. Thus, for outreach coordinators who target high schoolers, the names of promising students might be forwarded to deans and department heads at the outreach coordinator's home university. The university's department heads would then use these names to send out brochures describing opportunities for collegiate study at their institutions and notifications of other opportunities (e.g., federal agency-funded scholarships) they have at their disposal.

In this recruiting-centric paradigm, follow-on funding for outreach programs would be contingent on an adequate recruiting effort the prior year. The White House Office of Science and Technology Policy could coordinate a consistent set of metrics to define "adequate recruiting" across all agencies and outreach programs. The STEM community would come to understand exactly what it means "to recruit" and to abide by those guidelines.

After the federal agencies' reporting requirements are in place, Congress can ask GAO to monitor changes in the racial/ethnic/family income level participation in the outreach programs and also in the freshman classes of the STEM departments hosting the programs. If a positive change of more than 20 percent is noted in the programs, and more than 10 percent in the departments, then the program should be expanded.

To expand the program, Congress can first commission a study (e.g., through the RAND Institute or a similar organization) to map all public and private K–12 outreach efforts against all K–12 high schools in the country. Each high school would be tagged with the STEM programs that reach into it, with a notation as to whether recruiting

Table 9.1: A Sampling of Federal Agency-Funded K–12 STEM Outreach Programs

Name	Description	Funding	Participants
NASA Programs			
Aerospace Education Services Project[479]	Classroom and distance learning demonstrations; professional development		84,607 (students) 12,362 (educators) (FY09)
Education Flight Projects[480]	Hands-on research experiences in NASA facilities		775,148 (students) 20,990 (educators) (FY09)
Endeavour Science Teaching Certificate Project[481]	Professional development for STEM educators		40 (educators) (FY09)
INSPIRE[482]	Online learning community for STEM students		1,318 (students) (FY09)
NASA Explorer Schools[483]	Establishes partnerships with schools and families to improve STEM education	$4.57 million	85,004 (students) 3,442 (educators) (2008–2009 school year)
NASA Science, Engineering, Mathematics and Aerospace Academy[484]	Hands-on STEM education activities; Education Laboratory	$1.91 million (FY09)	40,471 (students) 18,945 (other participants) (FY09)
NIH Programs			
Science Education Partnership Awards[485]	Partnerships between researchers and education groups, including K–12 schools.	$21 million awarded in 2009	17 projects in 2009, 73 total
Curriculum Supplements[486]	Two weeks of teacher's guide material on the science behind health topics.	nearly $2 million (2008)	Over 250,000 requests to date
Blueprint for Neuroscience Research Administrative Supplement[487]	Extension to awarded grants for the purpose of reaching K–12 students and teachers about neuroscience topics. Includes educational games, materials, and professional development	$600,000 for FY2010 and 2011	Announcement just closed
NIAID Science Education Awards[488]	General support for creative and innovative programs that raise public awareness of biomedical research or encourage K–12 students to enter biomedical research fields of interest to NIAID	$345,000 (2008)	
4-H Adventure for Science[489]	NIH sponsors one of the locations where students from 8-15 spend Saturdays taking courses in various science topics		
NIST Programs			
Summer Institute for Middle School Science Teachers[490]	2-week program at NIST HQ to give teachers hands-on experience, ideas and resources to support their teaching. Some support provided for teachers to attend.	$40,000 in support for 20 teachers (2010)	
4-H Adventure for Science[491]	NIST HQ sponsors one of the locations where students from 8-15 spend Saturdays taking courses in various science topics		
NSF Programs			
Informal Science Education[492]	Supports innovation in STEM learning outside of school settings	$66 million (2008)	
Innovative Technology Experiences for Students and Teachers[493]	Focuses on research and tools that would most influence K–12 students into STEM careers. Informal experiences are an explicit target of the program.	$28.63 million (2008)	
Math and Science Partnership[494]	Universities partner with local high schools to design educational innovations, train teachers in delivering them to local high students, and measure performance outcomes	$42 million at NSF + $179 million at Dept. of Education	
DOE Programs			
National Science Bowl[495]	Lead sponsor of High school and middle school competitions on science and engineering topics	$2.03 million (FY2009)	17,000 students compete annually
DOE ACTS[496]	3-year program to expand STEM teachers experience through summer sessions at National Labs		229 educators (FY2009)
Department of Defense Programs		$4.13 million (FY2009)	
National Defense Education Program - Pre-College programs[497]	A variety of partnerships, teacher professional development, and summer programs		1010 teachers trained in summer programs, 7,300 mathematics clubs sponsored 500 students in summer programs
NDEP - STEM Learning Modules[498]	Inquiry Based learning modules for 24-32 students with help from DoD experts	$67.09 million (all of NDEP, FY09)	SLMs implemented in 20 states as of 2009
USDA Programs		see above	
Agriculture in the Classroom[499]	Coordinates state programs that provide agricultural resources for the classroom	$500,000 (approx.) (2009)	Programs in all 50 states

reporting is currently required for that program or not. This mapping exercise identifies remaining gaps that either the public or private sector need to fill. OSTP, in conjunction with state governments, philanthropies, and nonprofits, can then “fill in” outreach efforts to underserved high schools by persuading the funders of existing programs to modify their funding criteria; new criteria would include recruiting reporting requirements similar to those used by the federal agencies. The aforementioned efficacy data gathered by the GAO should help to make a persuasive argument that changing the reporting requirements yields real results.

Changing the reporting requirements ensures that outreach coordinators everywhere will make the effort to locate promising students, wherever they may be. Recruiting is critical to a STEM workforce strategy in which “Some STEM for All” is replaced by “All STEM for Some.” Every student who has the capacity or interest for STEM needs to be in the latter talent pool. Our pool of 5 percent to 20 percent of all students will be smaller than the “Some STEM for All” pool (100 percent of students), but the smaller pool will include those with a genuine interest, who can then much more effectively capitalize on advanced offerings and opportunities.

While the federal government is not in a position to do so, the above process could be further facilitated by nonprofits (particularly professional societies) willing to aggregate the names and contact information of the promising students. An entity such as the American Association for the Advancement of Science (AAAS) or the American Society for Engineering Education (ASEE) could collect names from outreach coordinators across all enrichment activities at all STEM institutions, and in turn make this information available to any and all interested parties willing to offer follow-on opportunities. The list of “promising outreach participants” could be augmented with the names of individuals who have scored very highly on national or state competitions (science bowls, robotics competitions) or standardized tests (state or national science or math tests). The system could become fairly automated, and provide a large identified talent pool from which to draw college students into STEM. Furthermore, this list of “America’s High School STEM Talent” could have corporate sponsorship, like the McDonald’s All American Rosters for NCAA football, thereby providing the revenue source needed to maintain the listing activity.

Videogame- and Software-Based Recruiting

But we don’t have to rely just on people to recruit students to go to the next level in science. We can rely on software and videogames. Videogames have enormous reach: *The SIMS* sold more than 100 million copies.[500] *World of Warcraft* has over 10 million paying subscribers.[501] Eighty-one percent of all youth aged 18–29 play videogames, with representation that is demographically proportionate across all major race and ethnicity boundaries.[502] Lesser-known titles, even in STEM, routinely access hundreds of thousands of players. *Wolfquest*, a National Science Foundation-funded game about ecology and the lives of wolves, has been downloaded 300,000 times and has 10,000 players logging on daily.[503] *Whyville*, a virtual world filled with math and science-themed games, has a user base of 5 million children.[504] *Whyville’s* core demographic is 8 year-olds to 14-year-olds, dominantly female.[505] Since *Whyville* is not formally offered through schools, this amazing population of would-be scientists is almost exclusively logging in from home in their spare time.

Parallel to the in-person recruiting scheme outlined above, videogames can offer a virtual recruiting tool with strong potential for talent identification. We make this argument based on the success of the U.S. Army’s recruiting game, *America’s Army*.[506] Launched in 2002, *America’s Army* has over eight million users, more than 15 times as many people as are in the U.S. army itself.[507] It has been downloaded over 42 million times and has absorbed about 321 million hours of active game play from passionate users.[508] In terms of exposure, *America’s Army* director Colonel Wardynski estimated that in 2005 that the *America’s Army* cost 10 cents per person-hour of exposure, versus $5 to $8 for TV advertisement.[509] Microsoft Executive David Edery and MIT researcher Ethan Mollick have claimed, looking at evidence after-the-fact, that the *America’s Army* game “had more impact on recruits than all other forms of Army advertising combined.”[510]

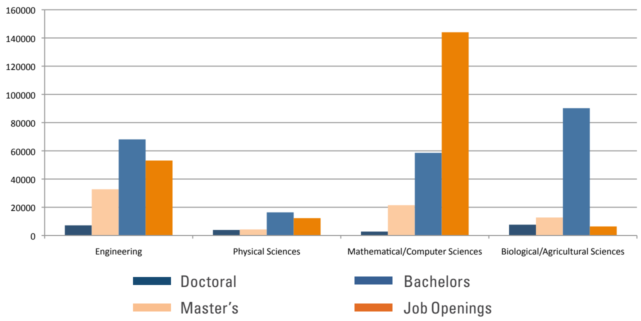
America’s Army does not feed directly into the Army’s recruiting system. Players participate anonymously, and therefore the rate of transfer from player status to new army recruit cannot be tracked. This is in part a consequence of federal funding, wherein it is difficult for a federal agency to obtain permission to track U.S. citizens. However, “America’s High School STEM Talent” list would be greatly enhanced if high scorers on science videogames could be included, given games’ enormous reach across all socioeconomic and ethnic communities. Individuals who post prolifically and intelligently on forums devoted to STEM videogames would be another source of talent (as per the Elitist Jerks forum mentioned in Chapter 5). We suggest, therefore, that the U.S. STEM agencies finance development of appealing recruitment games, but that the games then be handed off to an organization for maintenance and implementation as part of the talent tracking system above. This arrangement also provides an ongoing source of support to maintain the game, assuming the organizations are willing to accept advertising revenue on the game itself, which the government could not easily do.

Producing More K–12 Students in Specific Fields: The Challenge of Computer Science

Producing more STEM students is not enough. It is also important to produce more in a particular field where demand is likely to outstrip supply. This will require additional steps.

The computing sector, which employs workers in large numbers, is such a field.[511] IT is already a large employer (2008 data in Table 9.2), meaning any small positive change leads to large numbers of new jobs. Moreover, IT jobs grew more than four times as fast as all U.S. jobs between 1999 and 2008.[512] The Bureau of Labor Statistics projects that the computing sector will have 1.5 million job openings over the next ten years making this one of the fastest growing occupational areas.[513] Moreover, annual projected job openings in computer sciences (and math) are expected to be significantly higher than annual degrees issued, unlike other STEM disciplines. (Figure 9.1) If the United States were to put in place better policies to spur both digital transformation of the economy and an increase in U.S. global IT industry market share, we would need even more IT workers. Ensuring an adequate supply requires developing a blueprint for action that extends all the way back through K–12.

Figure 9.1: Annual Degrees, 2006 and Annual Projected Job Openings in Broad S&E Fields, 2008–2018[516]



Below we discuss the steps necessary to bring computer science training to K–12 in order to prepare future workers for IT jobs. While this approach is specific to computer science, its broad principles would apply to any STEM field needing large influxes of trained workers.

The Absence of Computer Science Education in K–12

During the past thirty years, computing has been at the heart of the global innovation revolution, creating entire new industries, transforming existing industries into productive powerhouses, and changing the face of culture across the globe. Computing is driving innovation in existing fields of science and creating entirely new ones. Underlying this revolution is the discipline of computer science. Paradoxically, as the role and significance of computing has increased in society and the economy, quality computer science education is noticeably absent in the K–12 education system. While there are many excellent K–12 computer science courses being taught across the country, consider these facts:

- Since 2005, the number of schools offering introductory computer science courses has declined by 17 percent, while the number offering AP computer science tests has fallen 33 percent.[517]

- The number of students taking AP computer science tests has been flat for the past decade while other science and mathematics disciplines have

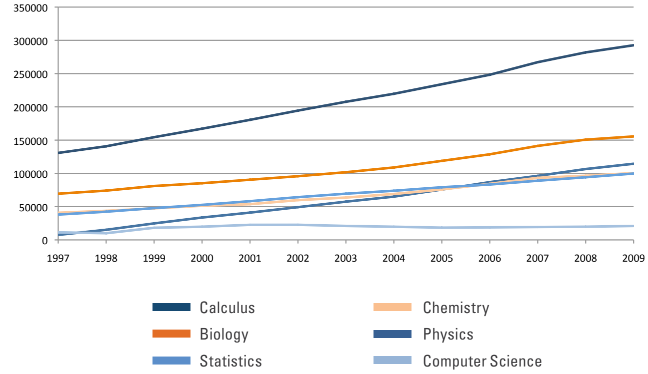
Table 9.2: Annual Degrees, 2006 and Annual Projected Job Openings in Broad S&E Fields, 2008–2018[514]

BLS Job Categories	2008	2018	Percent Change	Numeric Change	Total job openings due to growth and net replacements 2008–18[515]
	Total Employment	Total Employment			
Total, all occupations	150,931,700	166,205,600	10.10	15,273,900	50,928,500
Total, all computing occupations	3,792,000	4,606,900	21.49	814,900	1,504,100
Computer and information scientists, research	28,900	35,900	24.20	7,000	13,200
Computer programmers	**426,700**	**414,400**	**-2.90**	**-12,300**	80,300
Computer software engineers, applications	514,800	689,900	34.00	175,100	218,400
Computer software engineers, systems software	394,800	515,000	30.40	120,200	153,400
Computer support specialists	565,700	643,700	13.80	78,000	234,600
Computer systems analysts	532,200	640,300	20.30	108,100	222,800
Database administrators	120,400	144,700	20.20	24,400	44,400
Network and computer systems administrators	339,500	418,400	23.20	78,900	135,500
Network systems and data communications analysts	292,000	447,800	53.40	155,800	208,300
Computer and information systems managers	293,000	342,500	16.90	49,500	97,100
All other computer specialists	209,300	236,800	13.10	27,500	72,600
Computer hardware engineers	74,700	77,500	3.80	2,800	23,500

increased. (Figure 9.2) Three times more students now take the AP Art History test than the AP computer Science AB test.[518]

- There is a significant lack of ethnic and gender diversity among those who do take K–12 computer science courses.[519]

Figure 9.2: Trends in AP Exam-taking Over Time, 1997–2009



Moreover, many high school computer science courses teach students essentially computer programming—usually Java programming—with very little theory or "science" behind it. Most startlingly, these trends are occurring when national state and local policy makers are seeking to expand the capacity and quality of STEM education.[520]

How Current Policy on Core Requirements Undercuts New Fields in K–12

The reasons behind these participation declines are complex, with education policies, myths that computer jobs are going "offshore," and the false belief of many students that the field is uninteresting or focused on rote programming all playing varying roles. But among these, education policies play a key role. And these policies don't just hinder the development of a more robust computer science STEM education effort, they will hinder emergence of any new STEM discipline seeking to find its way into K–12.

There is an array of policy issues, but the most important is the widespread movement toward more required core courses.[521] As discussed in Chapter 6, a key component to current high school reform is to require more courses. Worried that students aren't learning enough of "X"? Simply require it. This core requirements movement is being pushed at both the state and federal level. Federal policy has created an environment where resources are focused on the "core" of what students must take to graduate. The No Child Left Behind Act (NCLB) created a new accountability structure for any K–12 institution receiving federal funds.[522] Students have to meet certain metrics based on standards in courses in mathematics, reading and science.[523] It also defined "core academic subjects" and tied some professional

development programs to this definition.[524] The practical effect of these provisions is that state and local resources are invested in the "core."[525]

Compounding this trend has been a push by many organizations for states to require that students take four-course sequences in English, mathematics, science, and social studies (sometimes called the "4x4" model) at the secondary level in order to graduate. This education standards and assessments movement has pushed disciplines like computer science outside of this ever-expanding core of required courses. The National Governors Association and Council of Chief State School Officers Common Core State Standards Initiative give states a common framework they can adopt for mathematics and English arts.[526] The National Research Council recently released a draft framework for science education, which seeks to identify the core content students should learn in four domains of science (including engineering).[527] Neither of these documents contain strands for computer science. With Department of Education's Race to the Top Fund and the Administration's Blueprint for Reform focused on fostering the common core movement, not being part of these efforts put computer science teaching at a significant resource disadvantage.

Computer Science Leads Innovation; Technology Literacy Follows Innovation

Another significant factor contributing to the current crisis in computer science education is profound confusion as to what constitutes computer science (CS) education or information technology education. Various studies and groups advocate for differing curricula and standards that further cloud these waters. Some have broad definitions of "technology literacy" that encompass many fields, some focus on computing or information technology certification, some focus on ensuring technology is used throughout the curriculum. National computing groups such as the Association for Computing Machinery (ACM) and the Computer Science Teachers Association (CSTA) argue for computer science standards and courses as part of the educational core for all students.

This swirl of terms is daunting to anyone trying to understand the integration of computing and technology in STEM fields and the work place. We offer the following definitions:

> Computer science—An academic discipline focused on the study of computers and algorithmic processes, including their principles, their hardware and software designs, their applications, and their impact on society.[528]
>
> Technology literacy and fluency—A spectrum of curricula ranging from literacy (understanding how to use technology) to fluency (the ability to express ideas creatively, reformulate knowledge, and synthesize new information and technology).
>
> Information technology courses—A broad and diverse set of topics, but typically focused on teaching how to apply the components of information technology, such as network or database administration and business programming.
>
> Educational technology or computing across the curriculum—The integration of technology into teaching in order to advance student learning across academic disciplines.
>
> Computing education—A broadly used term that, depending on the educational context, may encompass only one of the noted areas above to all of them and more.

All of these efforts have a place in K–12 education; the critical issue is understanding how they are related and how they are distinct. Goals to embed technology use in education or to ensure technology literacy are often focused on ensuring a basic knowledge of IT or a specialized knowledge (in the case of IT courses) of a narrow tool. These are clearly important skills considering the everyday uses of computing in the today's economy. However, such education, while important to providing all students with basic IT literacy, is not STEM education in the sense of helping to produce STEM workers. For pushing innovation in the software and IT industries, the preparation of computer scientists, rather than general technology literacy or the use of educational technology, is key.

Computer science education differs from basic technology literacy/IT goals in that it teaches fundamental concepts of computing, rather than its use via applications. An analogy might be that students can take either shop or physics to learn electronics. Thus, computer science teaching should sit on a continuum from basic computing concepts that can be attained at elementary and middle school levels to deeper knowledge, skills, and practices more appropriate for secondary school. Some of its topics overlap with technology literacy and IT curriculum, while some are completely different. For example, the complexity of algorithms is a fundamental idea in computer science but would probably not appear in a technology-literacy or IT curriculum. Even courses nominally called "computing" often do not teach algorithms. When "computing" courses are considered part of technology education, they often focus on post-secondary school vocations in information technology, such as network and system administrators or basic programming, versus the fundamental knowledge of computing that college-bound students need.

Paradoxically, as the role and significance of computing has increased in society and the economy, quality computer science education is noticeably absent in the K–12 education system.

Suggestions for Computer Science in K–12: Near-Term Strategies for Dealing with the Reality of Core Requirements

At a time when computing is driving job growth and new scientific discovery, it is unacceptable that access to computer science courses is limited because few states view computer science as a core academic subject, because no national method of delivering quality instruction exists, and because computer science teacher certification—our current method—is deeply flawed and inadequate in the numbers it produces. These are national failings and ones that we can ill afford in the digital age.

There are two approaches to redressing the lack of computer science in K–12 education. The first, obviously, is to define CS as part of the "core." This is the position taken by computer professional organizations like the Association for Computing Machinery (ACM) and the Computer Science Teachers Association (CSTA). It involves the least disruption to the current system, although it requires developing a new cohort of teachers and reeducating those that are already teaching "technology" or "computing" courses. Once CS is defined as a core subject, schools would be forced to offer—and resources would flow—to its instruction in K–12. And as long as the dominant approach to high school education reform is top-down mandates—in this case, core curricula, this approach is understandable. If you want to get CS into a curriculum that is inherently limiting and inflexible, the only way to do it is to join the process and require it along with everything else.

The education standards and assessments movement has pushed disciplines like computer science outside of this ever-expanding core of required courses.

The moderate-term approach as discussed in Chapter 5, is to abandon the notion of a fixed core of "knowledge" entirely, focus on skills instead, and allow students free exploration of topics that advance these skills and match their own individual interests and passions. In either scheme, computer science would reach far more students. In the core model, K–12 engagement with CS increases because CS is now required as part of the math or science core. In the free choice/no core model, computer science is not explicitly required, but because it naturally advances many skills—inquiry, design, and especially understanding/applying symbolic language—it would automatically qualify as a subject students could take to meet skills standards—without having to be separately "defined" in a government-approved list. In both cases, demand for CS courses should increase.

While our moderate-term recommendation is to abandon the concept of "core knowledge" altogether, and most of this report's recommendations speak to that point, it is instructive to walk through the steps needed to implement the shorter-term solution of bringing computer science into the current core. In the absence of large-scale strategic reform, concrete steps such as these will be necessary to bring any new field into K–12.

Create Quality Instruction

- Clearly define computer science education and organize it as an academic subject (particularly in secondary education). Congress can begin this process by including computer science in the list of core academic subjects currently found in U.S.C § 7801(11), with a notation as to what computer science means. Expand computer science education research at the National Science Foundation, which is often only focused on the "core" STEM subjects.

- States should adopt a well-defined set of K–12 computer science standards based on algorithmic/computation thinking concepts, such as those outlined in the ACM/CSTA model curriculum.

- The Department of Education should provide funding for the development of assessments in computer science education.

Deliver an Adequate Supply of Trained Teachers

- Base certification programs for computer science education only on the applicant's knowledge of the field, and how to teach it. Certification should be available to all qualified applicants, irrespective of the pathway the computer science teacher took to get into the classroom Offer alternative certification pathways to attract practicing computer scientists to teaching computer science.

- The Department of Education should create grant programs for higher education to deliver pre-service and professional development opportunities for computer science teachers.

Ensure Students Have Access to the Instruction and Teachers

- States and/or local districts (depending on state policy) should count computer science courses toward a student's core graduation requirements either as a computer science credit or as a mathematics or science credit.

- Using Department of Education resources, fund the development of one or more virtual curricula in computer science that can serve as a fallback for students who do not have qualified teachers in their schools.

These steps—create quality instruction, deliver an adequate supply of trained teachers, and give students access to both the instruction and teachers—are not particularly profound, and indeed form the basis of most STEM report recommendations. The real question is why haven't they been implemented for computer science? How can we still have so little K–12 capacity in computer science, after a decade of needing millions of computer scientists in the workforce? There are several reasons. One relates to the structure of public high schools, most of which are deeply conservative, doing what they have always done. Introducing completely new curriculum is not the norm. In addition, we did not make the leap from workforce needs to computer science instruction because it was no one's job to scan for major occupational shifts, and then link these to educational reforms.

A routine scan for major labor market shifts could be institutionalized by requesting that the Department of Labor biannually notify OSTP, Congress, and the Department of Education of any STEM field experiencing or about to experience a major expansion or contraction (defined as 500,000 new jobs or more over 10 years). OSTP, with Congressional funding, could then commission a policy body to coordinate the creation of a stakeholder-generated blueprint that moves from identified labor need to high-school curriculum inputs. Specific articulations of actors, roles, and proposed incentives would be included in this blueprint and provide a common framework for coordination. An analogy would be the SEMATECH roadmap process for the semiconductor industry, which successfully defined a goal for the industry, then proposed specific industry-government programs, industry milestones, and activities to meet those milestones, in order to recapture world leadership in semiconductor manufacturing.[529] The success of the SEMATECH roadmap lay in the fact that it was very concrete, was generated by those ultimately responsible for performing the work, and contained appropriate incentives for all actors. Such a blueprint for computer science would be an expanded version of the steps outlined above.

HOW CAN WE PRODUCE MORE B.S. STUDENTS?

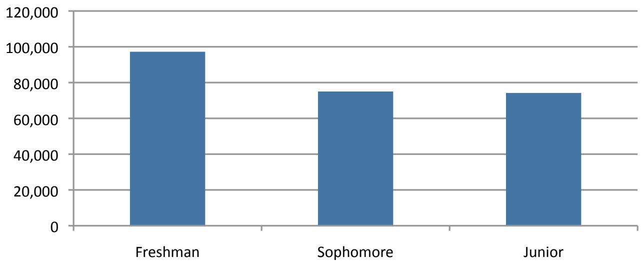
Clearly one way to produce more B.S. students is to produce more high school students with the skills and interests in STEM to want to major in STEM in college. But as noted in Chapter 4, this "Some STEM for All" approach is very expensive relative to results. A more cost effective way is to increase the share of STEM freshman who actually graduate with a STEM degree. According to the Department of Education, only 41 percent of students who enter STEM majors in higher education end up obtaining a STEM degree of some kind (certificate, associate's, bachelor's) after six years.[530] Of the remainder, approximately equal numbers drop out, as change to non-STEM majors. (Table 9.3)

Table 9.3: Disposition of Students who Enter STEM[531]

Entered STEM at some point between 1995-96 and 2001	**100**
Earned a degree in STEM (certificate, associates' bachelor's)	**40.7**
Obtained degree in original major*	28.5
Obtained degree in another STEM major*	12.2
In STEM 6 years later but no degree yet	**12.0**
Switched majors to something outside of STEM	**20.6**
Obtained a degree outside of STEM	14.2
Still in non-STEM major but no degree yet	6.4
Dropped out of school	**26.7**
(TOTAL)	(100)

When during the college process do we lose most of these students? Daempfle summarized several studies from the 1980's and 1990's to conclude that STEM students overall were either switching or dropping out at a rate of 35 percent between the first and second year, 2 percent between sophomore and junior year, and 8 percent from junior year to graduation.[532] This totals 45 percent of students leaving STEM over the course of their careers, consistent with the 47 percent combined rate of "dropouts" and "switch outs," shown in Table 9.3. The story is fairly consistent across sub-disciplines. According to NSF data from 1993-2007, the single biggest drop in engineering (a decrease of 23 percent) also occurs between the freshman and sophomore years, a phenomenon that has remained relatively constant over the last decade.[533] (Figure 9.3)

Figure 9.3: Average U.S. Enrollment in Engineering Programs[534]



The drop in STEM enrollment between the first and second year is troubling. Whether the disappearing students are "dropouts" or "switch outs" is not easy to pinpoint. Estimates are possible, though. Examining national trends in dropout rates across all subjects and institutions, we note that half of all eventual dropouts occur in the freshman year.[535] This allows us to estimate from Table 9.3 that about 13 percent of STEM students are probably dropping out of college that first year. This leaves approximately 21 percent of students who leave STEM their freshman year (or summer following) because they are switching from STEM majors to non-STEM majors. Moreover, relative to other majors, dropout is the lesser problem for STEM. Over a six year period, fewer STEM students dropped out of school than non-STEM students (26.7 percent vs. 32.8 percent).[536]

Switch out however, is a problem that plagues STEM more than other fields. Seymour and Hewett document that 44 percent of STEM majors switch out of STEM sometime in their college career vs. 30 percent of humanities majors switching out of the humanities.[537] (The STEM numbers would have been far worse had Seymour and Hewett included "health professions" and "computer/technical" in their list of STEM subject areas.) If we could eliminate switch out that first critical year, we could potentially increase the number of STEM graduates by 20 percent or more.

What about the freshman experience is so daunting? The extensive survey work of Seymour and Hewett across 7 universities found that "poor teaching by faculty" was cited as a concern among 90 percent of all students who switch out of STEM majors and 98 percent of students who switch out of engineering.[538] Of the 23 most commonly cited reasons for switching out of STEM, all but 7 had something to do with the pedagogical experience. "Curriculum overload, fast pace overwhelming," "discouraged/lost confidence due to low grades in early years," "inadequate advising or help with academic problems," "unexpected length of SME degree: more than 4 years," and "lack of peer study group support" were a few of these items.

It is possible to correct each of these deficiencies individually. For example, C's are rare grades in humanities courses, but commonplace in science courses.[539] At Cornell, one study found that the median grades in astronomy, chemistry, economics, mathematics, and physics were 0.2 out of 4.0 points lower than the median grade across all courses examined, which was 3.65.[540] A survey of seven other colleges showed introductory classes in chemistry, economics and math offered an average grade of 2.67, compared to an average grade of 3.03 for introductory courses in art, English, music, philosophy, political science and psychology.[541] Romer cites data from a College Board survey of 21 selective universities showing that the share of students in English classes getting an A or a B was 85 percent; A or B was earned by 60 percent of those taking history, and just 57 percent of students in math classes.[542]

... the share of students in English classes getting an A or a B was 85 percent; A or B was earned by 60 percent of those taking history, and just 57 percent of students in math classes.

Clearly these lower grades are not a result of the students taking STEM courses being less intelligent or diligent than students taking art. But the lower grades do spur more students to switch out of STEM. At Williams College, an analysis showed the probability of taking a second course in a given subject (English or Economics) was 14 percent to 18 percent less if the student received a B than if they received an A, and 20 percent to 27 percent less if they received a C than if they received an A.[543] Thus, one could eliminate discouragingly low grades in STEM, and boost student retention, by having the university mandate a "median grade" across all classes, colleges or majors.

Considering, however, how long is the list of deficiencies in the STEM learning environment, correcting each in turn is unlikely to be a "quick fix." We therefore focus our recommendations on providing one or two overwhelmingly positive experiences that can compensate for the slew of poor pedagogical experiences students are likely to encounter.

One of the dominant mythologies in STEM is that the students who switch out are those who are less capable. It is important to understand that it is the quality of the learning experience, not the quality of the student, which is at issue. Seymour and Hewitt's exhaustive examination of student attributes showed little difference between the aptitude, preparation or experiences of those who stayed and those who left.[544] The poor learning experience—the "gate" in the production of B.S. majors—was agnostic to ability: those switching out of STEM had GPAs very similar to those who remained (3.0 vs. 3.15).[545] Humphreys and Freeland report similar findings (3.10 GPA for switchers vs. 3.07 GPA for those who remained in STEM).[546] Seymour and Hewitt report that the same factors and concerns were articulated by both switchers and non-switchers, at roughly the same magnitudes. The only singular difference was that the "persisters" had a greater willingness or ability to "put up with" the poor learning environment:

> Perhaps the most important single generalization arising from our analysis is that we did not find switchers and non-switchers to be two different kinds of people ... What distinguished the survivors from those who left was the development of particular attitudes or coping strategies—both legitimate and illegitimate.[547]

In conclusion, a major "gate" in the production of B.S. majors is the poor pedagogical experience. This gate, however, achieves a reduction in quantity with no increase in talent. Because the reduction in quantity occurs largely in the freshman year, we recommend alternatives designed to increase the appeal of the educational experience during that year and suggest some incentives for universities to take these steps.

Rethinking Freshman Year Design

One way to reduce STEM switch outs (and drop outs) is to redesign the freshman year experience. In engineering, one successful approach to countering freshman-year dropout is to move the more interesting coursework, notably engineering design, into the freshman year. At the University of Cincinnati, a freshman design course was offered to introduce creative problem-solving early in the plan of study, eliminating a larger freshman class section.[548] Although retention numbers have not been reported, students overwhelmingly felt more strongly attached to the school of engineering and enthusiastic about their coursework. A similar program at Alabama A&M reported improvement in retention rates, from the freshman to sophomore years—from less than 50 percent before to more than 90 percent within a few years after implementing the design course.[549]

Student participation in research is another overwhelmingly positive experience, and one that—if relocated to the freshman or sophomore year—might significantly influence retention. One such program is the NSF Research Experiences for Undergraduates (REU) program. In a poll of NSF-sponsored undergraduate researchers, nearly half (48 percent) reported that it was "one of the best experiences of my life."[550] Seventy-five percent of NSF-sponsored undergraduate researchers also reported that they used skills learned doing undergraduate research in their job after graduation. And, finally, 29 percent of undergraduate research participants who didn't expect a Ph.D. before college, did expect one after the research experience.[551] A positive experience of this magnitude could counteract the otherwise negative pedagogical environment experienced by STEM students, and lead to retention. Daempfle arrived at the same conclusion:

> Student attitudes about faculty preoccupation with research and poor relations with students changed when students were allowed to participate in that research. The few students who had experienced this … valued the open relationship between faculty and student in a research situation compared with the faculty's apparent indifference to them in a teaching context.[552]

The obstacle that currently prevents undergraduate research experiences from reducing attrition is the student year in which they are offered. NSF's undergraduate research experiences programs (along with those provided by NASA and NIH) are designed to encourage B.S. students to move into graduate study. As such, they tend to target juniors and seniors—those closest to a decision regarding a graduate career. At any given point in time, roughly 60 percent of NSF-sponsored undergraduate researchers are seniors, 27 percent are juniors, 8 percent are sophomores and just 1 percent are freshmen.[553] In contrast, the greatest need for an anti-attrition agent is not in the junior year and following, but in the freshman year.

There is anecdotal evidence supporting the strategy of moving research experiences to the early years. The EXPRESS program at the University of Missouri targets research experiences to freshman and sophomore minority students. This program reports a freshman-to-sophomore retention rate of 90 percent, which is greater than for all students at the University of Missouri.[554] If a 90 percent retention rate from freshman-to-sophomore years is at all typical, retargeting and expanding undergraduate research experience programs to encompass nearly all freshmen could almost singlehandedly raise B.S. student production by 20 percent.

The obstacle that currently prevents undergraduate research experiences from reducing attrition is the student year in which they are offered.

Students at the Massachusetts Institute of Technology research in science laboratory.

Other efforts report positive results. The Howard Hughes Medical Institute established the National Genomics Research Initiative (NGRI), as a national experiment in both research and education that revolves around a research course in genomics for undergraduate students. In the program's first full year of implementation, 270 students from twelve undergraduate institutions—including large research universities and small liberal arts colleges—participated. NGRI students participate in an authentic research experience-integrated into a laboratory course designed for freshmen-that will result in a significant contribution to the broader genomics field. The program is intended to "inspire students before they have a chance to become bored or overwhelmed by the typical large introductory science course. Students will catch the spark of enthusiasm for inquiry-based discovery and absorb the process of doing real science at a point that will influence their whole college experience."[555]

Placing research experiences in the freshman year also allows the student, now "experienced" enough to be desired by industry, to take on industry summer or part-time jobs during the junior and senior years.[556] This chaining of academic and industry research has several positive benefits. It broadens the student, provides another source of student employment support, and promotes the diffusion of academic research into industrial application.

We therefore recommend that approximately one-third of federal-agency-funded undergraduate research experiences be moved immediately to the freshman year and summer following. Since there is no legislative mandate for these programs to be offered in a given year, this step could be achieved simply by Executive Order. Prior to the White House issuing the Order, OSTP can be directed to arrive at a list of programs that would be affected by such an order, and asked for process suggestions that would allow for a smooth transition to the new model.

Congress should also request a GAO study to determine the magnitude of the retention effect generated by such a relocation, as well as impacts on the decision to ultimately attend graduate school (the original intent of the research experience for undergraduate REU programs). The results of this study will then indicate how much the REU program would need to be expanded, in order to significantly reduce STEM freshman dropout and switch out. Congress can then take this recommendation into consideration for expanding the REU program.

Incentives for Universities to Reduce STEM Dropouts/Switch outs

One would think that there would be strong motivations for colleges and universities to take these and other steps to reduce switch out. It's not as if most colleges and universities don't know about the problem or the potential solutions. It's that for many there is only weak motivation to address the problem. Faculty may be concerned, but the reality is that budgets do not suffer: students who switch still pay tuition and still take classes that employ faculty. State schools still get their full-time equivalent—based money from state governments. From the perspective of the leadership of the college or university, switch outs have no negative impact on the institution. From the perspective of humanities and social science departments, switch outs help ensure that there are enough students to enroll in their classes. And science department size is already calibrated to a standard level of switch outs; if they really put in place practices to reduce it, the college or university leadership would likely not cut resources and faculty in the humanities and social sciences in order to expand resources and faculty in the hard sciences. Even students who drop out entirely are also replaced by students transferring in or by those in the upcoming class. As Stanford economist Paul Romer notes, "A liberal arts university that has fixed investment in faculty who teach in areas outside of the sciences and that faces internal political pressures to maintain the relative sizes of different departments may respond to this pressure by making it more difficult for students to complete a degree in science."[557]

Thus, unlike a business that downsizes a division whose products are not selling in order to expand output in the divisions whose products are selling, colleges and universities are less responsive to "customer" demand. This would not be a problem if America did not have such a stake in the issue. STEM college graduation exhibits what economists call an externality: STEM graduates produce innovations that are responsible for the lion's share of increases in U.S. standard of living. It is in America's interest to produce more STEM graduates, while most universities and colleges are largely indifferent to the issue of what people major in. With so many competing issues requiring time, attention, and resources, the only way to make STEM retention rise to the top of the academic "to-do" list would be to supply external incentives that provide hard backing to good intentions.

> **Unlike a business that downsizes a division whose products are not selling in order to expand output in the divisions whose products are selling, colleges and universities are less responsive to "customer" demand.**

Some government programs have attempted to do just that. As an example, the NASA-NSF Model Institutions for Excellence Program (MIE) expended $117M over nine years in order to increase the number of minorities in STEM fields. The program took place in six minority institutions and five of those programs demonstrated a modestly faster rate of STEM enrollment compared with other fields between 1997 and 2003 (25 percent STEM compared with 21 percent total). Success was attributed to the common program elements listed below:[558]

- Recruitment and transition initiatives prior to freshman year
- Peer mentoring
- Undergraduate research
- Scholarship funding
- Curriculum redesign

However, while the STEM degrees conferred at these institutions grew by 12 percent, the overall rate of enrollment increase about doubled. In other words, the conversion rate from enrollees to graduates, despite the list of institutional innovations, was still only half. Examining the data more carefully, it appears the major improvements were not stimulated by retention practices, but by creating STEM programs at institutions that had had none earlier. This was how enrollments managed to grow. Arguably, the national capacity for STEM education is already adequate to the national supply of willing STEM students. In this case, adding capacity at a few institutions might expand their STEM output, but primarily by shifting degrees from one institution to another. Adding additional capacity to a system that already has unused capacity would not expand the national pool of STEM B.S. degrees. Reducing STEM switch out would.

STEM Retention Prizes

The MIE example illustrates that standard strategies assumed to increase retention (recruitment and transition initiatives, peer mentoring, post-freshman undergraduate research, scholarships, etc.) have little effect, even in combination with significant funding (>$2M/year in the MIE case). However, these standard strategies are what pass most easily through peer review because they don't hold colleges and universities accountable for results or encourage them to do fundamentally different things. "Retention reform" may have to be radical to work. Therefore we argue that the best way to promote retention reform is not to ask institutions to reform, and pass the responses through peer review panels made up of other college officials, but to reward major gambles by institutions that have taken transformative steps and succeeded.

Specifically, we recommend giving a large cash prize to those institutions that have dramatically increased STEM student output and that can demonstrably sustain that increase over five years. Awards would be offered in three tiers: $5M for small colleges, $10M for mid-size, and $35M for large universities. The metric of merit would be the retention rate, defined as the number of students who have completed a B.S. degree in STEM over a five year period, relative to the total number of individuals who have entered the university over those same five years claiming "intent to major in STEM." If the initial retention rate is at least 50 percent and the progress made by the university in improving retention is equal to or better than 50 percent of the total improvement it could theoretically make, then the university would be eligible for a reward. The reason for rewarding relative progress, rather than absolute retention rate, is to ensure that even schools with high retention rates are eligible for the reward and will be spurred to make additional improvements. The "bar" for winning the award is relatively high so it's not likely that large numbers of institutions would win in any given year. However, if there is a concern about budget availability, a maximum number of awards could be set in any year, perhaps no more than three per category.

Let's assume that for college A, 30 percent of freshmen enter intending to major in STEM, but only 15 percent receive degrees (a completion ratio of 50 percent). The college could improve to achieve 100 percent retention. If after five years, 40 percent of entering students intend to major in STEM, and 30 percent receive degrees (a ratio of 75 percent), the college got exactly halfway to the total improvement it was possible to obtain. This college would just barely be eligible for an award.

The list of STEM fields covered under this competition would comprise the NSF-designated list of natural science (including computer science) and engineering disciplines (psychology would not be included). In the baseline years prior to the institutional innovation, at least 50 students per year would have to graduate in STEM from that college or university for the institution to be eligible. To retain eligibility, the absolute number of students graduating in STEM could not dip more than 15 percent during the institutional experiment (otherwise, the temptation would be to reduce an entering class of 500 to an entering class of the top 150 achievers, in order to obtain greater retention down the road).

Once the awardee pool routinely began to reach the cap of what funding would allow, the competition would end—mission accomplished. However, it is important that in the interim, every university embarking on a change program knows that if it succeeds, it will win the award. The uncertainty should be limited to the gamble on the internal investment in radical new practices, not the gamble on whether success, if achieved, will be rewarded. If need be, disbursements can be delayed to the following year, if too many applicants win in a given year. Any college or university that wins the award would have to agree to comply with requests for information (within reason) from institutions seeking to emulate its success.

To establish this program, Congress would appropriate $100 million a year to the National Science Foundation, for five years, ideally to be matched 1 to 1 by a major philanthropy. Funds would accrue for five years until the competition period begins; annual awards of up to $200 million would be made until the funds are completely expended.

Expand Government R&D Expenditures

One way to expand the supply of STEM students is to expand demand for them. While supply-side strategies are important (and indeed this report is focused principally on them) it's important to note that demand does play some role in inducing supply. In part, this is because decision making by individuals is influenced by market signals, and the U.S. government has an enormous hand in generating these signals. STEM student output mirrors government R&D expenditures, even more so than industry R&D expenditures. At least until the mid-1980s, growth in industry R&D tracked the growth of STEM B.S. degrees. But in the late 1980s it didn't, and in the last 15 years the relationship has been less robust. (Figure 9.4) In contrast, there is a closer relationship between student outputs and government R&D expenditures. (Figure 9.5) At a finer-grained level, the relationship between federal funding and student output continues to hold, and even sharpen: Figure 9.6 tracks just the federal funding to the non-biological sciences (physical sciences, math and engineering), and compares this with student outputs in those same fields. Here, the bump in R&D funding due to the Apollo missions and manned space flight, also begin to be seen in the student curves as well.

Figure 9.4: Industry R&D Expenditures and B.S. Student Output, 1953–2007[559]

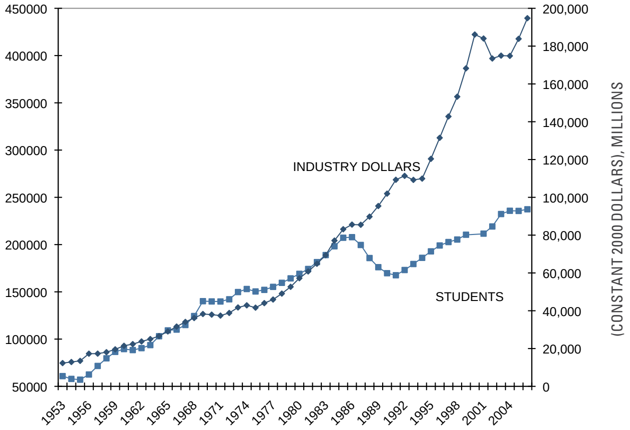


Figure 9.5: Federal R&D Expenditures and B.S. Student Output, 1953–2007[560]

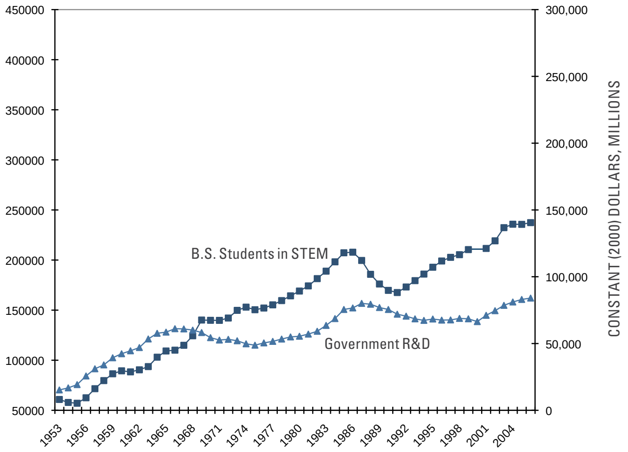
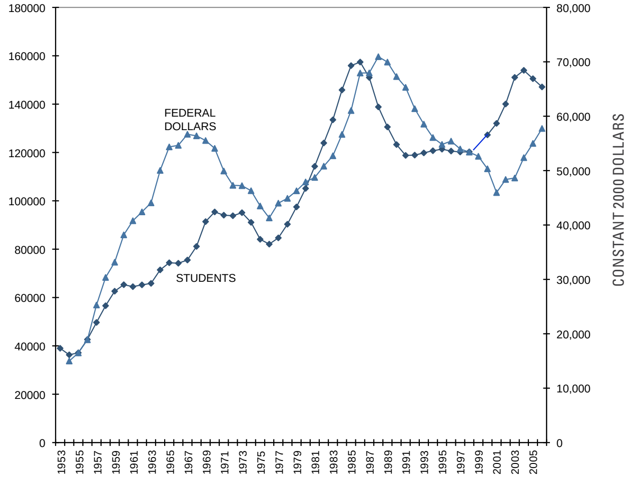


Figure 9.6: Federal R&D Expenditures and B.S. Student Output in Physical science, Math and Engineering, 1953–2007[561]



While the relationship is not perfect (in some cases changes in the student curve precede the funding curves), there appears to be a correspondence that is quite good in statistical terms. An earlier analysis of the correlation coefficients between physical science, math and engineering students, and the federal funding related thereto yielded a correlation coefficient of R2=0.95 for the 1953–1968 time period and a correlation coefficient of R2=0.84 for the 1970–1998 time period. Generally an R2<0.3 is considered a weak correlation, an R2>0.6 is considered a strong correlation, and an R2>0.9 is characteristic of a "law" in the physical sciences.[562] An interesting point to note, especially with respect to Figure 9.6, is that the two large bumps in the government "dollars" graph are due to acquisition or contract dollars, not research dollars. In other words, these are dollars given by government to industry specifically to create cutting edge hardware and software. As noted earlier, student output mirrors those bumps. We posit two reasons for this effect. First, the creation of real jobs—especially jobs localized to the United States—sends market signals to the students that are obvious even by neoclassical standards (higher wages, lower unemployment). This drives individuals to major in STEM fields and/or to persist in STEM studies despite obstacles. Second, acquisition programs that demand hardware with new capabilities can and do reach back into the university system to draw out innovations, thereby adding to the financing of university research, university departments, and the continued production of students. This kind of R&D is different than the incremental innovation often financed by corporate R&D. Thus, the partnering of long-term, visionary, government-led objectives with practical, on-the-ground implementation and hiring appears to be an effective combination for pulling students into STEM.

The data in Figure 9.6 also yield insights as to the most effective mechanism by which to attract students using acquisition funding as the driver. In the 1960s, government undertook and was the prime executor of a major acquisition program (manned space flight). In the 1980's, the government undertook an acquisition program (strategic defense initiative) with industry as its prime executor. In both eras there was very strong correlations between government funding and STEM student graduation but exhibit vastly different student outputs per unit cost: 1.03 students/$million in the government-executed project vs. 2.46 students/$million in the industry-executed project. Arguably, the hardware itself was much more of a stretch in the case of the Apollo missions, and should have cost more, but from the standpoint of just the students produced as a byproduct, the more cost-effective route would have been to fund industry.

In conclusion, a direct and powerful way to quickly expand B.S. degrees in a given field is for the government to fund major research, development, testing and deployment systems, preferably from industry suppliers. Conversely, government attempts to convince students to major in STEM through fellowships, curriculum redesign, and other enticements will be facing an uphill battle at times when government (and industry) R&D expenditures are decreased, sending the opposite message through labor market signals. A solid workforce policy would therefore encompass a coherent strategy, from identification of the opportunity, to increased R&D funding to send the correct overall labor market signals, to implementation of the other strategies outlined in this report to generate students in the right numbers, with the right skills, and at the right times.

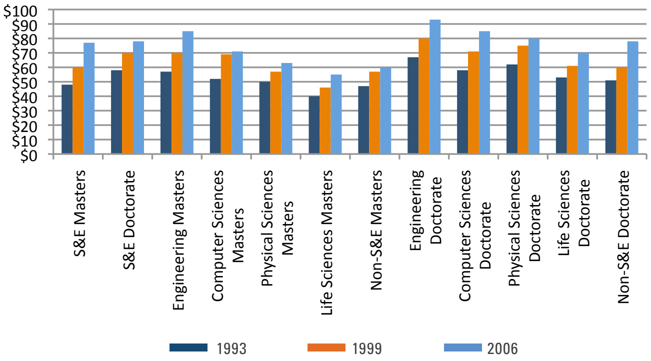
HOW CAN WE PRODUCE MORE MASTER'S STEM STUDENTS?

Producing more master's students is probably the easiest of all tasks; there are plentiful market signals pointing towards a national need for more master's degree STEM students. The primary "gates" for STEM master's degrees appear to be insufficient programs designed with industry in mind (as opposed to the academic-track master's) and insufficient transparency to allow industry to find, recognize, and hire students coming out of the industry-oriented programs.

Over the last 13 years, there has been a substantial increase in the median salaries for S&E master's degree holders relative to S&E doctorate holders. (Figure 9.7) By 2006, the salary of a master's degree holder in S&E had approached that of a Ph.D. student in many fields. In fact, one to five years out from degree, the engineering, life sciences, and computer sciences master's students are actually earning more than corresponding Ph.D.s.[563]

Given employer demand, as evidenced by high starting salaries, a supply-side solution to producing more STEM master's students should work. This was the approach taken by the Sloan and Keck Foundations, who worked not just to create more master's degree programs in the United States but also to redesign them as Professional Science master's (PSM) degrees to better meet industry demand (57 percent of STEM master's students are employed by industry compared to 31 percent of Ph.D.s).[565] As opposed to traditional science master's programs, these "science plus" programs integrate high-demand science courses (about 70 percent) with management and business courses (about 30 percent), producing a more complete skill set needed for most industry jobs in industry.

Figure 9.7: Media Salaries for Master's and Doctorate Holders (in thousands)[564]



The Sloan Foundation initially gave grants to 14 research universities in 1997 to establish PSM programs, while the Keck Graduate Institute of Applied Life Sciences enrolled its first students in 2000. There are now 195 PSM Programs at 96 institutions in the United States. But the programs are relatively small, with about 2,600 students enrolled annually.[566] These programs gained federal support, as funding authorized in 2009 by the American Recovery and Reinvestment Act (ARRA) enabled the NSF to distribute $15 million for creating 21 new PSM programs around the country.[567] The results of new program creation, specifically designed around industrial employment, have been even higher salaries of the professional Science master's, above even those of traditional STEM master's degree holders.[568] In 2003, starting salaries for new hires with any master's degree in the biological sciences was $40,000, the physical sciences $49,000, and mathematics and statistics $54,000. PSM graduates in these fields, on the other hand, had starting salaries of $45,000 to $55,000 in nonprofits and government, and $55,000 to $62,000 in private industry.[569] The higher salaries strongly suggest that the skill sets produced by these degrees are in high demand.

The fact that these Professional Science master's programs were able to continue successfully, once underlying financial support from the Sloan Foundation was terminated (as in the case of the Sloan PSMs) suggests, additionally, that there is already a baseline level of demand from the tuition-paying students. Moreover, enrollment demographics suggest that these redesigned degrees are attracting a more diverse set of students. Statistics from all PSM programs show that they access pools of talent beyond those reached by "standard" master's programs: they enroll 50 percent women and 10 percent underrepresented minority groups (in contrast to 36 percent women and 7 percent URMs for all STEM graduate enrollment).[570]

The level of enrollment, though, could be expanded much further. The 2,600 students in PSM programs represent only 0.6 percent of all full-time S&E graduate students. Demand from employers is high (as evidenced by salary offers) but generally limited to those "in the know": 20 percent of all students hired from Keck's PSM program are hired by one employer—Amgen.[571] Fixing the signaling between employers and students—so employers are more widely aware of skills students have to offer, and so students feel their "unusual" degree title has broader market recognition among employers, would help expand enrollment further. For this purpose, we recommend the foundations supporting PSM degrees (Keck and Sloan) embark on an employer awareness program.[572] Separately, implementing a system by which employers would hire according to evidenced skills, rather than degree labels, would open up a large market for PSM graduates having desirable skills but as-yet unrecognizable labels. This would be the national skills credentialing system outlined in Chapter 11.

Once employer awareness is improved, market demand should help to support the expansion of PSMs. The initial role of the government thus becomes one of closely monitoring today's market signals (salaries and employment rates of master's students in different fields) and ensuring that fields with strong need are met with additional programs until the need appears to be satisfied. Foundations would complement the federal activity with promotional advertising to employers. An evaluation of the results of the NSF investment in producing PSM programs via the 2009 ARRA funds will be part of the process of monitoring local demand.

If and when local market signals demanding more master's students become muted, but national priorities dictate an expansion, other strategies for increasing master's student production will be necessary. This second set of solutions will look very similar to what we propose below for Ph.D.s.

HOW CAN WE PRODUCE MORE STEM DOCTORAL STUDENTS?

One key way to expand the number of American residents receiving STEM Ph.D.s is to expand financial support for their education. Indeed, the science policy community has frequently advocated for increasing the number of available federal graduate fellowships.[573] For example, *Rising Above the Gathering Storm* recommends that the federal government increase funding by 5,000 new graduate fellowships per year.[574]

The iconic model inspiring many current fellowship programs, and motivating calls for more of the same, is the National Defense Education Act (NDEA) of 1958.[575] The NDEA was passed in response to the launch of the Soviet satellite Sputnik 1. One of NDEA's central provisions, Title IV, established the National Defense Fellowships, which offered financial support for young students desiring to enter Ph.D.-track graduate programs.[576] These fellowships were noted for exerting "considerable influence on the growth of graduate education in a number of states which had produced no doctoral graduates or very few up to that time."[577] A recent study shows that Title IV significantly increased the number of doctorates amongst lower income students, while also decreasing the average time to degree (presumably due to reduced financial burden).[578] Although the National Defense Fellowships program is no longer in effect, it retains wide recognition for its perceived impact on the research community.[579]

Unfortunately, federal support for doctoral fellowships has declined as a share of GDP. The number of NSF graduate research fellowships awarded per thousand of college students graduating with degrees in science and engineering went from over seven in the early 1960s to just over two in 2005.[580] Today the same numbers of NSF graduate research fellowships are offered per year as in the early 1960s, despite the fact that the number of college students graduating with degrees in science and engineering has tripled. [581] (Figure 9.8)

To reverse this trend, the Obama administration has proposed increased funding for research fellowships. The 2011 science budget provides fellowship funding of $158 million to the NSF, $824 million to the NIH, $15 million to the DOE, and $40 million to the DOD; these quantities represent increases of 16 percent, 5 percent, 10 percent, and 4 percent, respectively, over the preceding year's fellowships budget.[582]

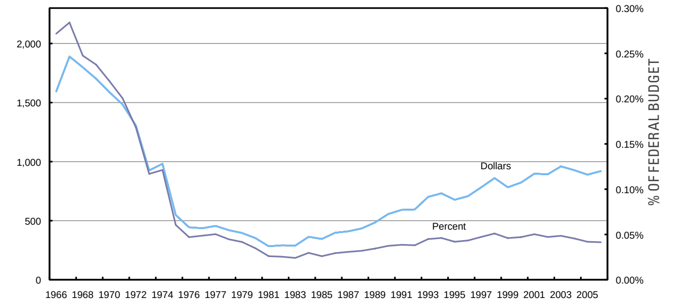
Clearly, the science policy community has reached the consensus that fellowships are vital to the strength of the STEM talent pipeline. But do more Ph.D. fellowships in fact create more Ph.D. students, even in this day and age? The answer appears to be yes. Harvard professor Richard Freeman examined 50 years of correlation between the budget of NSF's graduate fellowship program and the number of applicants it receives. He concluded that a 10 percent expansion in the fellowship program's budget yielded a 41 percent increase in applicants. More importantly, Freeman showed a subsequent correlation with enrollments. The same 10 percent increase in NSF graduate fellowship program budget leads to a follow-on increase of 7 percent—15 percent in actual Ph.D. enrollments. In other words, creating 2,000 new awards directly translates into 2,000 additional Ph.D. students. Providing fellowships to individuals to obtain their Ph.D. does work, and Freeman argues that increased fellowships are the most direct way to increase the pool of Ph.D. graduates. However, he cautions:

> … it is difficult to determine if the increase in awards attracts students on the margin of going into science, or if the increase goes largely to students who would study science and engineering in any event.[583]

In order to evaluate the true effectiveness of these incentives in attracting the "best and the brightest" (vs. just another student), it is first necessary to consider the funding environment of graduate school in the absence of a fellowship. Unlike many professional post-undergraduate degree programs (which require students to shoulder most of the financial burden of matriculation), modern STEM doctoral programs are generally funded through outside sources, such as research or teaching assistantships, which ultimately derive from research grants or educational funds. The federal government offers one billion dollars in combined fellowship and traineeship support for students. (Figure 9.8) However, fellowships and traineeships combined account for only 17.7 percent of all supported graduate students; research assistantships account for 30.4 percent, teaching assistantships for another 39.4 percent, and other outside support for 12.6 percent.[584] Because of all these external support mechanisms, only 6.6 percent of doctoral students at "research universities with very high research activity" use personal funds as a primary support mechanism. If one includes all doctorate-granting institutions, the number rises only to 10.4 percent.[585] In summary, relatively few STEM graduate students must "pay their own way" through graduate school, and non-fellowship sources of funding provide the support for most.

The financial incentive of the fellowship is the monetary difference between the fellowship stipend and the stipend of these alternative sources. The three most common pre-doctoral fellowships are those of the NSF, the NIH, and the DOD which pay respectively $30,000, $21,180, and $30,500 in their first year, with additional allowances of up to $8,400 available from NIH.[587] The awards also carry cost-of-education allowances—tuition, fees, training, etc.—that go directly to the institution, rather than to the student. While these may sound like substantial sums, they offer limited additional financial incentive above standard graduate-level stipends. A recent survey of graduate stipends in biological Ph.D. programs shows 36 to be stipends of $26,500 per year or greater, signifying a fellowship pay incentive of approximately 15 percent or less.[588] Many of these programs are amongst the top-rated ones in the nation.[589] Notably, seven of these programs paid $30,000 or more per year, effectively matching the fellowship stipend level.[590]

Figure 9.8: Federal Funding for Graduate Student Traineeships and Fellowships, 1982–2010[586]



Students who are competitive for fellowships are likely to attend top-tier research universities, where research assistantships are readily available. A recent evaluation of the National Science Foundation's Graduate Research Fellowship found that 94 percent of the fellows selected from 1989-1993 attended RU1 research institutions (ones that grant over 50 doctorates a year), and receive over $40 million in federal grant funds.[591]

Not only is their financial incentive modest with regard to other options, fellowship awards do not factor into being admitted to a preferred graduate school—which might otherwise be an incentive. Fellowship announcements are made too late in the process to be a factor.

In the end, with similar incentives and similar pathways, graduate fellows end up being little different from their peers, as concluded in an analysis of NSF's graduate fellowship program:

> Graduate students in the same academic programs are quite similar to each other. Most NSF fellows attend programs whose reputations are among the highest in the country and where admission is highly competitive. For example, both NSF fellows and [non-fellow] peers have high GRE scores, especially quantitative scores. NSF fellows have stronger verbal and analytic scores than peers. In some programs, especially Biochemistry, no distinctions between NSF fellows and peers were either reported or observed …[592]

The fact that fellows are indistinguishable among a larger company of peers can also be illustrated by comparing outcome data from different quartiles in the fellow selection process: top-rated fellows ("Quality group 1,"or QG1) can be compared with their second-tier fellows (QG2), whom were judged as less qualified than their QG1 peers but received the same funding. The non-funded QG2 students (those receiving an "honorable mention") provide a non-fellowship control. Of fellows starting in the period from 1984 to 1988, 49 percent of top-rated fellows finished their Ph.D.s' within six years, versus 44 percent of QG2 fellows and 41 percent of second-tier non-awardees.[593] Using an 11-year completion window, the numbers reach 75 percent, 69 percent, and 65 percent, respectively. For the time period of 1989 to 1993, more QG2 non-awardees actually finished within six years than QG2 fellows (39 percent to 41 percent, respectively), with only a slight advantage for top-tier fellows (43 percent). [594]

After graduation, the fellows also face the same pressures as their peers; hence, the defection rate from academia is high for both fellows and non-fellows. The report cited above highlights limited job opportunities, high competition, excessive lifestyle demands, low compensation, and disillusionment—discouraging features that are likely faced by all graduating Ph.D. students going into academic careers:

> We found that career choices shift during graduate school. Many graduate students become less inclined to pursue academic careers as time passes. Both NSF fellows and peers are increasingly likely to pursue careers in government, business, and industry, and most respondents indicated their primary responsibilities were research and development.

Ultimately, the ability of modern fellowships to convince undergraduates to choose graduate school over other options is limited, due to the minimal financial incentive, the nominal reduction in time-to-degree, and the wide availability of alternative research funds in top-tier Ph.D. programs. The primary advantages of a fellowship are more freedom in choosing a research project (not being financially beholden to a specific advisor) and less time spent helping to teach courses and/or earning support through other means. A third advantage is the prestige offered by the fellowship, which could be translated into increased visibility in a hiring pool later on. Nevertheless, the data show these positive benefits are not substantial enough to attract a cadre of students that is substantially different from the peer group of other STEM students applying to the same universities. For this reason we argue that fellowships need to be restructured to attract more top-tier students in the face of attractive career alternatives.

Ph.D. fellowship programs should therefore be expanded, but also redesigned to attract the highest quality students. From the days of the National Defense Education Act to the present, fellowships have expanded the Ph.D. pool and can be increased in number to achieve that purpose yet again. We recommend a $21 million increase to NSF's Graduate Fellowship program matched by industry in order to accomplish this expansion goal. (See Chapter 10)

At the same time, any increase in the number of fellowship recipients should be accompanied by a strategy that attracts quality above that of the broader peer group, and innovative individuals who seek a path above and beyond that of a "standard graduate student." Presently there are no differentiators that would cause this to be the case. For this and other reasons, we recommend that the NSF Ph.D. Fellowship program be redesigned to add a "guaranteed job interview" promise to fellowship recipients, under a unique Memorandum of Understanding arrangement between NSF and industry. A direct pipeline to a job would be a singular incentive not offered to scholarship or traineeship recipients, and should attract more highly qualified candidates. In addition, the analysis here suggests several additional untapped incentives that could be employed to attract higher caliber talent:

1. Provide a significantly (25 percent to 50 percent) higher stipend for fellowship recipients than research assistantship and trainee recipients.

2. Issue the fellowship award notifications prior to graduate school application deadlines (i.e., before December of the year prior to graduate school entry). This allows the fellowship to influence which graduate school the recipient chooses to attend—another plus, from the student point of view.

3. Offer fellowship recipients unusual enrichment opportunities, as is done to attract highly qualified freshmen to undergraduate honors programs: a chance to visit with the President's Science Advisor or tour a nuclear submarine or convene in a virtual town hall with the science attaché of a country that has been in the news. One can build a virtual community of fellows that adds a socio-intellectual dimension to the award, beyond the cash provided.

Increasing Ph.D. fellowships should increase Ph.D. student output. Better-built incentives should also tilt the fellows applicant pool to more exceptionally qualified individuals. However, incentives work only if people know about them. Ph.D. fellowships are known best by those who have heard about them through word of mouth via parents or professional mentors. The lack of any visible marketing campaign is probably resulting in a "quantity" gate that has little to do with intrinsic STEM skill, but rather with the extent of one's social connections, particularly to responsible adults already in the STEM research community. We postulate that large numbers of additional individuals may have no idea that fellowship, traineeship, or even research assistantship support exists, much less that the funds are sufficient to provide both free tuition and salary support (stipend) during the Ph.D. years. For highly qualified individuals outside the STEM social network, career decision-making is not being incentivized by the possibility of obtaining financial support. A premed student with M.D. parents may not realize that a free Ph.D. is a viable alternative to tens of thousands of dollars of medical school debt.

A poll to determine how many undergraduate students (or their parents) are aware that Ph.D.s are largely paid for, may yield opportunities for market development among federal agencies wishing to lure students into advanced STEM study. We recommend such a poll be conducted. The results would indicate how much difference a "Your Ph.D. degree is free!" (or similar) campaign might make to the quality and quantity of Ph.D. program applicants. The poll might also indicate how much more Ph.D. support programs could be expanded, beyond their current base, and still attract qualified applicants.

In Chapter 10 we take up the fellowship topic again to discuss how redesign of existing fellowships can be used to influence pipeline skill mix, in addition to the quantity goals pursued here.

CHAPTER 10:

Getting the STEM Skills Match Right

Spot shortages in labor markets can arise in the short run for multiple reasons. As discussed in Chapter 3, salaries for STEM workers are high, but not as high as in some border-constrained professions, like doctors and attorneys. Therefore, conventional labor market signals, such as salaries, may not be high enough to lure some STEM workers into jobs to fill temporary shortages. The workers, while nominally trained and available, may potentially have more attractive opportunities in other industries.

Information asymmetries also play a role in creating spot shortages. Industry's needs are not well transmitted through the university system to the student, with the result that students cannot respond by taking appropriate courses or choosing appropriate majors. As Romer notes, many STEM university departments do not provide students with adequate information regarding the job search or potential jobs after graduation, let alone information about internship programs. He further argues that the entire menu of skills taught in our universities may not align well with the skills that are in demand in industry.[595] Likewise, Bardhan, Hicks, and Jaffee find a considerable lag in the responsiveness of higher education to the changing occupational needs of industry. While some STEM degree programs are more responsive than others to changes in labor market demand, especially computer science and electrical engineering, others, including biological sciences, are not very responsive, and "the overall system of higher education in the United States is only moderately responsive to labor market signals."[596]

... industry—with government help—needs to engage students directly, during their academic years, through fellowships, co-op positions, internships, and other exposures to industry.

Spot shortages result when students emerge in adequate numbers overall, but with different qualifications than those industry needs. We argue that industry—with government help—needs to engage students directly, during their academic years, through fellowships, co-op positions, internships, and other exposures to industry. Students who intimately understand what they will need to know on the job can choose more appropriate majors, select among course options more accurately, and demand new courses where none exist. In this manner industry can better apprise students of job needs in the marketplace.

TRANSMITTING INDUSTRY NEEDS DIRECTLY TO STUDENTS

Without a strong communication conduit from industry to students through academia, some industry needs will never be transmitted to students or universities. Such needs are also not transmitted through the press. For example, defense companies generally must hire U.S. citizens since they need employees who can obtain security clearance. However, the need for security-clearable programmers is drowned out by press reports of programming jobs being shipped offshore. As a result, there tend to be shortages of programmers who are U.S. citizens, likely because many individuals do not understand that niche (U.S. citizen-only) positions are available.[597] Similarly, high-end applied mathematicians have been sought after by the banking industry, often to no avail. Despite the proliferation of computational finance degree programs, jobs for "quants" are open to anyone with a rigorous enough mathematical background, regardless of degree title, and pay up $150,000 to 250,000 a year salaries with only a bachelor's degree, if the skill set is there.[598]

There may not be 50,000 quant jobs in the United States, and therefore the shortage is not worthy of a newsmagazine spread, but the "point of the spear" driving banking innovation is nevertheless missing. In this instance, for example, there needs to be a systematic mechanism whereby the banking industry can address its STEM human resource needs through the nations' mathematics departments.

Create Industry-University Fellowships

One method of reducing spot shortages caused by the weak link between academia and industry is to offer industry-government-cosponsored fellowships. Financial commitment by industry is important, because it allows industry to broadcast a public message regarding the seriousness/magnitude of the need. Industry's financial engagement also creates a heretofore absent feedback loop linking industry's workforce needs, the student's course selection, and funding agency fellowship dollars. Government cost-sharing of these positions is also important, as it ensures that student training will continue uninterrupted by stock market crests and dips.

A major source of current government fellowships in STEM are the NSF graduate research fellowships. However, as discussed in Chapter 9, there has been a significant decline in fellowships in recent years. But rather than simply expand funding for the NSF Graduate Research Fellowship program (funded at $102 million) to do this, Congress should instead create a new NSF-industry Ph.D. fellows program. Currently the NSF Ph.D. Fellows program provides up to three years of support over a 5-year period and supports approximately 3,400 students per year at $40,500 per year.[599] The new NSF-industry program would work by enabling industry to contribute $20,250 towards each fellowship, in whatever field(s) the company chooses. NSF would match industry funds dollar-for-dollar.

If Congress allocates an additional $21 million to a joint industry-NSF STEM Ph.D. fellowship program, NSF could support an additional 1,000 graduate fellows, all of whom would be tuned to industry needs. If, after three years, it turns out that industry does not adequately support the program, or students and universities are not interested in the program, then it should be terminated with the funding redirected into the regular fellows program. For those who worry that industry funding will taint the scientific learning process, it is important to remember that students would be guaranteed the funds only as long as the university agreed the student was performing up to its standards.[600] Moreover, as Denis Gray has documented, industry-university partnerships have no negative effect on academic freedom.[601]

Alternatively, or in addition to, the co-funding scheme described above, NSF and industry could coordinate their efforts so as to give preferred job placement for NSF Fellows. This, too, would be a significant carrot for premium candidates. Specifically, NSF could enter into a Memorandum of Understanding (MOU) with a pool of companies interested in receiving graduates in a specific field. That MOU would ask each company to guarantee two job interviews to each NSF fellow in that field: a formative interview, to provide a sense of industry needs prior to the fellow's course selection for a Ph.D., and a second, "real" job interview as the fellowship is wrapping up. The job itself would not be guaranteed by this process, but the job interview would be. The prospect of having guaranteed job interviews as part of the Fellowship package would be a very attractive complement to the current fellowship program and require little to no expenditure by NSF or industry. It also provides industry with a way to steer course and research topic selection by our nation's best and brightest, and gives industry direct access to these students after they graduate.

The insertion of industry experience into graduate training would also alleviate growing concerns about the disconnect between the training that graduate students receive and their future job responsibilities if they choose to enter the private sector for employment.[602] Most doctoral programs still train students as if they were all destined for academic careers. However, in STEM, this view is myopic and often more wrong than right. For example, one survey of doctoral chemistry students found that only 36 percent intended to go into academia (compared to 76 percent of English students).[603] As Campbell, Fuller, and Patrick have argued, "graduate education needs to be broadened from its research focus to include a wider range of training for the careers students are pursuing and to reflect the versatility needed to work in an increasingly global job market, where collaboration between industry, universities, and government agencies is the norm rather than the exception."[604] An integrated government-industry fellowship system places our federal funding agencies into a direct, actionable dialogue with industry concerning industry's human resource needs. This feedback loop is invaluable.

While the fellowship model with industry experience is here presented as a Ph.D. option, it may be that the direst industry need at any given point in time is for niche expertise at some other skill level (B.S. or M.S.). The same model could obviously apply at these skill levels as well. Of note, the Department of Homeland Security, the National Science Foundation, the Department of Defense, and the National Institutes of Health already offer B.S. level fellowships (though, at the B.S. level, they are called "scholarships").[605] Industry-giving at the B.S. level also exists but is coordinated through professional societies and trade organizations, such as American Institute of Aeronautics and Astronautics (AIAA), Society of Automotive Engineers (SAE), and Society for Mining, Metallurgy, and Exploration (SME), to name a few.[606] Federal agencies can therefore issue an RFP to professional and trade organizations, asking them to retool their existing undergraduate scholarship programs to incorporate an industry experience, and offering up to $5K in matching funds (per-year, per scholarship offered) in return. This then should spread the practice of establishing industry-relevant experiences in STEM education.

Innovative, industry/government/foundation/association partnerships that stretch education "outside the ivy box" can be explored and funded via a mechanism that does not pass through peer review and therefore does not enter confrontation with the traditional academic mindset. The NSF EAGER (Early-concept Grants for Exploratory Research) mechanism would be well suited in this regard.[607]

While not directly related to industry-sponsored STEM fellowships, the recommendations provided in Chapter 7 to create more interdisciplinary connectors would also have an impact on skills mismatches. If more graduate school research is involved in partnerships with industry, through programs like the Industry University Cooperative Research Program, students are more likely to understand the emerging labor market needs in industry. A model program that does this extremely effectively is the Focus Center program sponsored by the Semiconductor Research Corporation and co-funded by the Defense Department. (Box 10.1)

Create More Industry Coops, Internships, and Summer Jobs For STEM Undergraduate Students

Another option to improve links among industry, academia, and government is to encourage the creation of more industry-rich co-ops, internships, and summer jobs. These kinds of experiences typically occur at earlier stages in the college student's life than do (Ph.D.) fellowships. In Chapter 9 we argued that hands-on/"real-life" experiences should be widely available early in youthful careers because of their prophylactic effect on student dropout. Here we argue that because industry-centered experiences are the most direct way to orient young students to industry needs, we should modify policy to expand such industry-centric offerings to youth.

BOX 10.1: THE SEMICONDUCTOR RESEARCH CORPORATION: AN INDUSTRY-LED PROGRAM THAT EDUCATES THE FUTURE TECHNOLOGY WORKFORCE

Thirty years ago, the U.S. semiconductor industry faced challenges from overseas competition. In response, visionary industry leaders formed a nonprofit consortium, the Semiconductor Research Corporation (SRC), to invest in and manage long-term research addressing industry's technology needs and to create a pool of experienced university researchers and a pipeline of graduates knowledgeable about semiconductor science and technologies. Based on alignment of industry and government needs, including for a robust technology workforce, SRC has established research programs that are jointly funded with DARPA, NSF, and the National Institute of Standards and Technology.

SRC has had a substantial impact on both industry and academia. SRC investment has built a network of more than 1,000 university collaborators working in the semiconductor field. Materials, design tools, and processes based on SRC research are widely used across the industry. Just as significant as the technological output has been the impact on human capital. SRC has supported over 8,400 graduate and undergraduate students, almost all of whom remain in the semiconductor field as researchers and innovators.

SRC-supported students receive an enhanced education. First, because SRC attracts and funds the best researchers from across the country, students are part of the top research teams at top universities. Second, students benefit from working on industry-relevant research, learning about real-world applications of science and engineering principles. And third, they are mentored by industry scientists and engineers and have other industry interactions, for example, at reviews and conferences and through internships and co-ops. Connections with industry are a hallmark of SRC student programs. As a result, SRC students are highly sought after for employment upon graduation.

While the quality of SRC students is very high, SRC member companies would like there to be a greater number of non-U.S. science and engineering graduates with the permanent right to work in the United States and more input from underrepresented populations, including women. To grow the pipeline of such students, SRC created a Ph.D. fellowship program open to U.S. citizens and green card holders and a master's scholarship program open to women and underrepresented populations who are also U.S. citizens or green card holders. These programs provide generous support and have graduated hundreds of outstanding scientists and engineers, many of who have gone on to become leaders in the field.

In addition to supporting graduate students, SRC is expanding support for undergraduate students through its Undergraduate Research Opportunities (URO) program. The URO program aims to retain physical science and engineering students by providing hands-on research experience and mentoring, and to encourage them to apply to graduate school and pursue an advanced degree. It also offers opportunities for industry contact, including internships and attendance at SRC conferences. Although open to all, the program reaches out in particular to women and students from other underrepresented populations. With funding from the Intel Foundation, the URO program supports about 230 students annually. In the 2009-2010, more than 40 percent of URO students were women and approximately 30 percent were African-American or Hispanic, significantly higher than the percentages in the U.S. physical science and engineering undergraduate population as a whole.

SRC research and SRC students are inextricably linked; one would not exist without the other. The connections forged among students, faculty, and industry working together on SRC research are long-lasting and are at the heart of SRC's success in sustaining U.S. leadership in the highly competitive semiconductor industry.

*This box was based on material provided by Dr. Celia Merzbacher, Vice President-Innovative Partnerships, Semiconductor Research Corporation."

Move Summer STEM jobs and Internships from Government-Sponsored Facilities to an Affiliated Corporate Setting

At present, there are hundreds of government-sponsored "temporary work" opportunities for STEM youth, but these are situated primarily in government, or government-funded university laboratories. A typical example would be the Department of Homeland Security HS-STEM Summer Internship Program. This program is a 10-week summer internship that provides opportunities for students to conduct research in DHS mission-relevant research areas at federal research facilities. Each award is for $5,000 over a 10 week period.[608] Programs such as these provide opportunities for students to be exposed to interesting STEM areas, but they do little to tune students directly to industry needs. Utilizing the same amount of government funding to place students in industry is arguably a more direct mechanism of introducing STEM students to the workforce. For example, DHS funds could be used to place students in companies that are DHS suppliers or collaborators, rather than federal laboratories. This approach still tunes the student to "meet DHS needs" while also providing invaluable industry connections and experience. Students who ultimately end up working for industry, will be all the better prepared; those who end up working for DHS, will have benefitted from formative industry experiences that help solidify connections between DHS and the world outside DHS. We recommend that OSTP lead an effort that identifies existing government scholarship/internship programs in which students are hired into government laboratories/facilities and matches them with companies relevant to the government's overall STEM mission, that are willing to place students in their facilities instead, for at least one summer or semester.

Provide Companies Tax Incentives for Sponsoring STEM Students in Temporary Work

Part of the overall challenge in creating temporary jobs for students in industry is that jobs requiring high levels of professional expertise (engineer, scientist) also require long learning curves. For this reason, they require intense mentoring for the student to accomplish anything significant, time that industry managers and workers can ill afford to give. Student positions in industry do not exist in large numbers, and where they exist at all, they are generally limited to juniors and seniors (who may possibly have enough training under their belt to produce something of value over a summer, without too much supervision).

From a policy standpoint, though, the need for students to engage with industry is most acute in the freshman year or the following summer, when they are at the highest risk of dropping out. This is, after all, why we recommended federally funded student experience programs be retargeted to the freshman year. The same principle applies here, but more so. Moving industry internships to the freshman year would not only impact dropout/switch out rates but also give career feedback at the point in the students' careers when they are most able to apply a course correction to their educational path, to more accurately match industry needs. The question then becomes, how do we make industry co-ops, internships, summer jobs, etc., more available generally, but especially to less-well-trained freshmen and sophomores without burdening industry in the process?

Because a key barrier to industry's hiring more students is the commensurate loss of time from existing valued employees, we recommend that the time spent by any industry professional serving as a mentor to temporary student hires be considered a charitable deduction by the IRS, similar to a direct donation by the company to a university. The student being claimed for the "donation" must have been enrolled full time at an accredited institution for at least six months during the year the apprenticeship/co-op/internship/summer job takes place. The company could claim up to 35 percent of the aggregate student hire hours as donations of employee time, at the median prevailing wage of their salaried employees. In addition, the government could offer grants wherein companies serious about establishing large student training programs could have some of the student salary costs offset. While the government may pay around $5,000 per student via either approach, the return on investment would be large, considering the same individuals will be paid $50,000 and up by industry upon graduation. Assuming an effective personal income tax rate of 20 percent, the government would be reimbursed within six months of the student's graduation—and continue to be reimbursed the students' entire working life. The alternative, losing this job to an overseas contractor whose training is better aligned with industry, or losing the student to a less well-paying degree major, results in $2-$10K/year of lost revenue to the government.

Match Freshmen and Sophomores to Middle-Skills Technical Jobs

There is another option, though—one that could bring university-generated innovators to large, heretofore untouched sectors of our economy. We could make freshman and sophomore STEM students the summer hires of choice for middle-skill jobs. Middle-skill jobs are jobs that require some education beyond high school, but not a full bachelor's degree. According to a number of sources, middle skill jobs will be a major growth area in the next decade. For instance, Judy and D'Amico suggest that 65 percent of all jobs in 2020 will be middle skills jobs, but only 32 percent of all workers with be adequately trained for these positions.[609] More recently, Holzer and Lerman conclude that a substantial demand remains for individuals to fill skilled jobs in the middle of the labor market; they report that roughly 45 percent of all job openings between 2004 and 2014 will be in the middle-skill occupations.[610] Specifically, they predict a 0.7 percent increase in the population educated to take these jobs, but more than a 10 percent increase in the jobs themselves. Even in the current recession, states like New Mexico are reporting too few of their residents are trained to fill their largest job category, namely middle-skill jobs (49 percent of jobs in this category vs. 45 percent workers).[611]

Middle-skill jobs include occupations such as accountants, calibration and instrumentation technicians, aircraft mechanics, and medical laboratory technicians. What is interesting about this list is that one can construct a parallel list of STEM occupations, at the B.S. level and higher, in the same areas. Replace the items in the above list with: mathematician, electrical engineer, aerospace engineer, and medical researcher. In short, B.S. students pursuing the higher level jobs upon graduation may be qualified to take on the middle-skill jobs before that time, as summer or co-op positions. These jobs are often seasonal (many are affiliated with the construction industry) and require short learning curves—ideal for students on break.

Historically, universities have had almost no relationship with middle-skills employers, because these jobs are not targeted at the B.S. level and above. From the student's point of view, however, middle-skills jobs pay extremely well compared to working retail at the mall and provide "real" hands-on experience. Temporary placement in middle-skills jobs could solve the problem of linking experience to education for B.S. students—particularly those too early in their careers for professional co-op and summer job placements. Students who find there are 100 summer positions in HVAC installation may get the message that there is a strong industry need for designing better thermal management systems, and begin to think about these problems during their studies. Students who install cable modems over the summer might likewise begin to conceptualize consumer needs in home router networks. The increased traffic between soon-to-be highly educated students and some of the mid-skills occupational sectors should push the frontiers of innovation even more in these sectors. A case in point is the career of Harry Heltzer, CEO of 3M from 1966-1972, who obtained a B.S. in metallurgical engineering but began his industry career as a laborer in 3M's abrasives department. It was his invention of reflective glass beads, now used in highway signs and highway striping, that generated an entire new business line for the company, and launched his progression up 3M's career ladder.[612]

For all of the above reasons—better pay and experience for the student, better quality short-term labor for the industry, better feedback between the education system and major occupational sectors, and more innovation for large sections of our economy, we recommend that colleges and universities begin to establish summer, co-op and other temporary job programs for their students with middle-skills employers. The phenomenal rate of youth joblessness that occurs during recessions argues for pursuing such an approach even now.[613]

Temporary stints in industry should become an integral part of student life, both at the professional and middle skills level. However, our current system for delivering such experiences is random and unorganized, with the primary gate being the social network of the student. Companies rarely advertise STEM summer jobs in particular; many are worried that if they do they would receive thousands of (unqualified) applicants. Consequently, companies limit advertisement of summer openings to notices on their own websites, emails to existing employees (who may have children eligible for these positions) and word of mouth. This approach reduces the applicant pool to a manageable level. However, any system that relies primarily on social networks will exclude those outside the network, thereby narrowing and homogenizing the pool of students who are "available" to work at any one company, typically to employees' children or employees' friends' children or students at the employees' alma mater. Far preferable would be a system in which all interested students in the country would be on display to all potential employers, and vice versa, such that a best-fit match can occur.

A model might be "The Match," i.e., the National Resident Matching Program, used by the medical profession to assign medical residency slots.[614] To construct a "STEM Match" platform, we recommend that the government issue two Requests for Proposals (RFPs)—one asking for a lead organization to construct a matching system for scientist-type temporary placements, and another soliciting a matching system for engineering-type temporary placements. The key factors in choosing a "winner" would be evidence that the lead organization has a track record of generating substantial industry participation in its projects, and has a partner capable of delivering the software solution. Once constructed, each match system would be maintained through student and employer posting fees.

A match system broadens the applicant pool without deluging the employer with thousands of resumes. It also highlights the relative state of supply and demand in different industry sectors, making job market realities explicit to students while they are still in training, and while they can still modify their career paths.

CHAPTER 11:

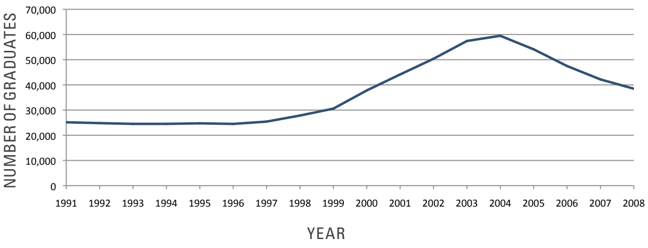
Getting the Timing Right

Separate from the industry-student communication issue, which hinders students from being directed to fields in which jobs are available, the STEM workforce has a timing problem: the four to eight years it takes to get a degree, vs. the half-year or so typical business cycle. Engineers, and to a lesser degree, scientists, are employed by companies that sell products or product-related services. The fortunes of these companies can change dramatically in an economic downturn—or upturn. Students who receive job-relevant information from industry still may not be able to redirect their training fast enough to correspond to the pace at which world events can suddenly overwhelm that industry. The same swings in fortune do not plague doctors and lawyers as much; such services are needed regardless of economic conditions.

Ultrafast industry growth outpacing student production timelines is one scenario in which time-lag effects are seen. In the case of the dot.com boom, the IT industry was expanding so rapidly that the education system, while responding, could not build up workers fast enough to meet the ballooning need. The four years needed for a B.S. degree was simply too long. For example, from 1991 to 1997, the number of graduates in computer and information sciences did not fluctuate significantly. However, in response to the dot.com boom from 1995 to 2000, the number of graduates started to increase in 1997, gradually gathering steam until roughly 60,000 graduates were being produced by 2004. While this is a positive outcome in some sense, the long student production timeline meant that student production peaked, not when industry need peaked, but four years after the dot.com crash of 2000. (Figure 11.1)

The long timelines for student production mean not only that our labor supply can't catch up with fast-moving industries, but also that newly graduated labor is sometimes out of sync with demand in cyclic industries. For businesses such as metal refining or recycling (demand depends on cost of raw ore), aerospace engineering (demand depends on periodic issuance of large government acquisition contracts), or petroleum engineering (demand depends on price of oil), to name a few, students can't be produced fast enough to satisfy momentary price/contract fluctuations. When such fluctuations are large, they send strong signals that are met by students entering the field—who sometimes find no jobs once they have graduated if the boom has passed.

Figure 11.1: Graduation Rates in Computer and Information Sciences[615]



To keep the innovation economy humming in good times and bad, to ensure "every worker has a job and every job has a worker," and to eliminate spurious negative signaling between the economy and STEM student production, we propose a set of solutions designed to address short-term worker needs: a much more responsive immigration system, a better means of locating existing skilled workers onshore, and implementation of an industry worker "reserve" system.

MAKING IMMIGRATION MORE TIME-RESPONSIVE

The H-1B visa is the primary means by which technology companies hire skilled foreign workers to fill spot shortages. The H-1B visa was created by the Immigration Act of 1990. The maximum number of new visas issued per year is set at 65,000, although beginning with the 2005 fiscal year Congress allowed 20,000 additional visas for foreigners who earned an advanced degree at a U.S. university. However, demand for H-1B visas is so high that the annual cap has typically been met before the fiscal year even begins. For instance, the H-1B visa cap of 65,000 was over-subscribed on the first day that applications were permitted in 2008 and was also fulfilled within the first week that applications were permitted in 2009.[616] Trying to find the "right" number of H-1B visas has been a political quagmire, with advocates for raising caps pointing out the industry need, and advocates for lowering caps pointing out jobless engineers. The political quagmire then leads to time delays that often make visas appear when they are needed the least. For example, the H-1B visa cap hit its maximum of 163,600 in 2001, in the midst of the dot.com recession.

If Congress is unwilling to raise the caps to higher levels on a permanent basis, having an on-demand mechanism to quickly raise H-1B visa caps at certain times will allow fast-growing industries to capture market advantage and continue to grow, thereby assuring future jobs in the United States.

If Congress is unwilling to raise the caps to higher levels on a permanent basis, having an on-demand mechanism to quickly raise H-1B visa caps at certain times will allow fast-growing industries to capture market advantage and continue to grow, thereby assuring future jobs in the United States. Raising caps quickly, without extended debate, is also unlikely to harm U.S.-based workers. Research by Mithas and Lucas shows that throughout the years of the H-1B visa debate, H-1B visa holders were complements to, rather than substitutes for, U.S. workers in the IT industry.[617] These researchers show that the salaries of H-1B-visa holders were about 7 percent higher than those of U.S. citizens, after controlling for educational attainment and work experience. Raising the H-1B caps diminished the premium (for example, down to about 3 percent in 2001, because of the larger available pool of H-1B workers) but never erased it.[618] Thus, foreign workers are competing amongst themselves, and not with U.S. citizens, for jobs the U.S. citizens are not qualified to fill. Another data point showing that H-1B visa holders are not "cheap substitutes" for U.S. labor comes from the 2001–2003 era. During this economic downturn, industries seeking to cut costs had every opportunity to import foreign workers if indeed they were "cheap replacements for domestic workers." But they did not. Instead, during the 2001–2003 dot.com bust, the H-1B visa caps were never even approached.[619]

A more recent study by Kerr and Lincoln also examined the effects of the variation in H-1B visa caps on employment and innovation.[620] They did not find any substantive effect of H-1B caps on U.S. STEM workers across a range of labor-market outcomes, including employment levels, mean wages, and unemployment rates. The study also ruled out crowding-out effects and actually observed the potential for small crowding-in effects. For instance, Kerr and Lincol reported that a 10 percent growth in the national H-1B population corresponded with about a 0.5 percent higher growth in total STEM employment.[621] One reason for this is that H-1B workers enable U.S. companies to be more competitive in global markets.

The fact that H-1B workers are complements, and not substitutes, for U.S. workers is a critical observation. It explains why there can be jobless engineers at the same time industry is crying for workers—the two groups of workers do not possess the same sets of expertise. It also points out that we have large structural deficiencies in our education and workforce system; there are areas of need where even higher salaries would be paid to U.S. workers, if only they had the proper expertise. Long-term planning to meet those needs, (e.g., through the industry-aligned fellowship programs in Chapter 10) is needed.

However, expanding H-1B worker supply during brief periods of shortage also makes sense: it appears not to damage U.S. workers, keeps companies in the United States competitive, and minimizes the salary premium U.S. companies have to pay for foreign workers. We just need to ensure H-1B visas are issued in the right quantities, at the right times, to meet industry needs.

At present, H-1B visas are set by a political process whose timeline (and outcome) are often completely out of sync with employer needs. We argue the system would be more responsive if we allowed the H-1B caps or fees to float directly with the unemployment rate. For instance, when the unemployment in a certain sub discipline is low, the caps would automatically be high, while in periods when the unemployment rate is high, caps would be lower. Caps would reset automatically each quarter as new unemployment data become available.

Alternatively, one could eliminate caps entirely and just set the H-1B visa fees to fluctuate with employment rate: in times of low domestic unemployment, H-1B fees would also be low, and it would be inexpensive to bring in H-1B workers. At times of high domestic unemployment, fees would be higher (e.g., 20 percent to 30 percent of annual salary), so only a modest number of the most desperately needed workers would be brought in. The floating fee system would have no caps. It says, "If U.S. workers are already being taken care of, you can import your foreign talent. If not, and you are truly desperate—if this is really the next Einstein you're talking about hiring—then even though many U.S. citizens are unemployed, you can pay a premium, and we will let you have the person you need." A floating fee system could reassure a skeptical, unemployed public that no, the company is not trying to replace U.S. workers with "cheap" foreign substitutes. And, unlike the current system, where in some years all visas are used up the first day they are offered, at least industry could get the workers it needs. And, from the industry perspective, it is routinely paying a premium for foreign talent anyways (about 7 percent of annual salary); it might not matter if that same premium were rendered to the U.S. government as a fee instead.[622] Ideally, funds collected from these fees would be dedicated to NSF STEM fellowship programs.

As of this writing, the Senate is considering a measure to authorize a commission to recommend levels of employment-based visas and green cards that let immigrants work legally in the United States.[623] We propose that this commission consider a system that allows H-1B caps (or better yet, fees) to scale with unemployment levels. This commission's job in setting the size of the national labor supply would then be similar to that of the Federal Reserve in setting the size of the national monetary supply. The Federal Reserve increases/decreases interest rates to tighten/loosen the monetary pool within the United States on a quarterly basis. The "H-1B Visa Commission" would increase/decrease visa fees to tighten/loosen the labor pool within the US, also on a quarterly basis. All money is the same, so the Federal Reserve sets only one interest rate, but all occupations are not, so the visa commission would have to set a number of fee rates, one for each sub discipline. Otherwise, the roles of the two bodies would be very analogous. If a commission is not appointed to oversee H-1B visa rates and caps, this job could be delegated to the Department of Labor, by Congressional authorization.

MAKING DOMESTIC WORKER PRODUCTION MORE TIME-RESPONSIVE

Many STEM-trained workers don't work in jobs requiring STEM knowledge. Roughly 48 percent of bachelor degree holders in STEM report working in a job that is in the same broad field as their degree; 16 percent report working in a related field, and 37 percent in a job that is unrelated to STEM.[624] Many of this last 37 percent might be convinced to return to STEM if the right job came along. Unfortunately, these out-of-fielders are probably not lined up at college recruiting centers or other obvious locations waiting to be offered a job by STEM employers. Their current job label will also be a deterrent for headhunters looking to fill a STEM job vacancy.

Added to this pool are individuals who have STEM expertise, and who may actively want STEM jobs, but whose degree labels would never indicate as much: those who are self-trained (e.g., the 16-year-old programming whiz living in his parents' basement), those who come to the United States with unfamiliar degrees (e.g., degrees from Russian universities), those with no degrees (not-quite-graduated, e.g., "all but thesis"), those with confusing degrees ("B.S. in Homeland Security Engineering"), and those with work experience in lieu of a degree (25 years of designing aircraft). How can employers find individuals like these who may be qualified when the principal tool they have to recognize STEM workers is the degree label? Or perhaps they had a degree at one time, but now it's doubtful, 20 years hence, how much of that skill set has been retained? Or the specialty needed is one so new it doesn't even have a degree label yet? Or the specialty is so common—like advanced mathematical training—that employers find themselves looking across computer scientists, physicists, engineers, and mathematicians?[625] How does the employer sort through the labels to find the right person?

This problem of finding the right people in the larger pool of "STEM-qualified" is a systemic problem that skills-based credentialing and hiring can address. In a skills-based credentialing and hiring system, the employer does not advertise jobs by their conventional descriptive label ("chemist") or degree ("B.S."), but specifically by the skills required for the job ("job requires level 5 applied math, level 3 teamwork, level 4 knowledge of organic chemistry"). On the applicant side, it is now possible to apply for such a job simply by testing into each of the required skill areas: if you score a 5 or better you are by definition a qualified applicant, even though your conventional label may say "Associate's Degree in Journalism." In times of human resource scarcity, this system provides employers with the widest possible pool of potential applicants—and a way to find unusual skill blends not even dreamt of in university departmental silos.

There are benefits to the applicant, too. Individuals can move between fields far more freely, and they are typically much closer to a new job than in a degree-based system: if the applicant is missing a new job opportunity by 1 level of applied math, he now only has to train up a bit in that one skill, not go back and get an entirely new four-year degree, in order to replace his Journalism label with an Engineering label. Headhunters can now look across an enormously wide range of industries, from banking, to manufacturing, to national intelligence, to find that special individual who scores the very rare "7" in applied mathematics.

This skills-based approach to locating employees is being used currently in some settings through the WorkKeys skills credentialing system. (Box 11.1) It tests for the foundational skills required by a wide variety of jobs, including science and engineering. The three basic WorkKeys tests cover the "learn how to learn" skills, as described in Chapter 5. Other skill tests are typically layered on top of this, as the manufacturing sector has done for its advanced jobs.[626] We argue that the return on investment by other sectors in using this approach is so high, that it is time to test out the concept of skills-based hiring and credentialing for STEM.

While WorkKeys has mostly been implemented in non-STEM jobs, it could be applied to STEM. Many STEM positions require most of ACT's testing suite of 9 skills tests (see skill requirements for a computer systems analyst, Table 11.2) to be accurately described. Thus, STEM employers will, in most cases, not be able to accept a career readiness certificate itself as evidence of job-readiness. They will need to have each job category in their company separately profiled (a cost of $1,500–$3,000), and screen for applicants according to the entire suite of skills that job requires. In locations where career readiness certificates are common, but job profiling is not, this will mean advertising for applicants who already have the correct fundamental skills scores, but then bringing those applicants in-house for a day to finish out the remainder of the tests.

Table 11.2: WorkKeys Skills Scores for A Computer Systems Analyst[631]

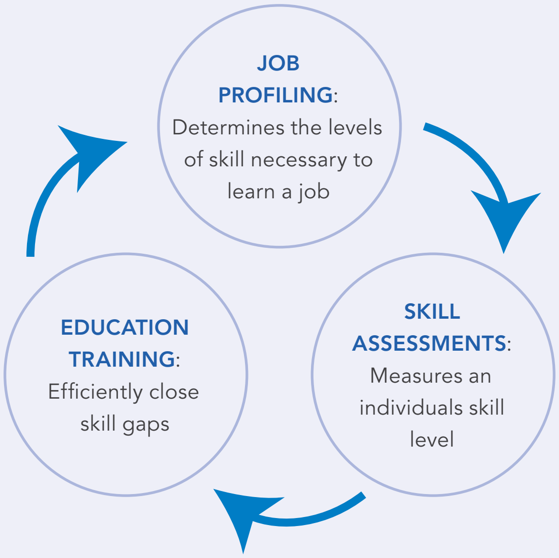
Applied Matematics	**Listening**	**Locating Information**	**Workplace Observation**	**Reading for Information**	**Teamwork**	**Writing**	**Business Writing**
3	5	4	4	5	4	3	4

Another gap between WorkKeys and a true skills-matching system for STEM is that many employers expect some level of content knowledge to accompany the skills. The ability to read complex diagrams will show up in WorkKeys tests, but not whether the individual was specifically trained in phase diagrams, as most material scientists are. For these kinds of knowledge-related requirements, one can, however, use existing knowledge-related tests. Examples include Cisco's Certified Network Associate tests (for expertise in computer networks), the Oracle database certification exams (for database administration), Apple's certificates in areas such as editing and sound design, the Fundamentals of Engineering (B.S. level content knowledge in engineering) and PE (graduate-level content knowledge in engineering) exams administered by the National Council of Examiners for Engineering and Surveying, the GRE exams (for biology, chemistry, cell and molecular biology, and physics), and more.[632] The list of appropriate exams for STEM occupations is substantial, in large part because either companies (in

BOX 11.1: SKILLS-BASED CREDENTIALING AND HIRING: THE WORKKEYS STORY[627]

ACT Inc., the company that provides the nationally accepted ACT college entrance exam, created a way to assess workers' foundational skills and provide reliable, relevant information about workplace skill levels. The WorkKeys system is composed of three parts; assessment, job profiling and skills gap education and training. (Figure 11.2)

Figure 11.2: WorkKeys Assessment System[628]



The first part of the system is assessing skills. One might think that there must be thousands and thousands of skills required in the jobs of today. However of the 16,000 jobs profiled nationally using WorkKeys, about 80 percent use three foundational cognitive ability skills: applied mathematics, reading for information, and locating information, albeit at varying levels of proficiency.[629] (Table 11.1) Six personal skills are also common, and are similar to the 21st Century skills employers say job seekers need: listening, teamwork, writing, performance, talent, and fit. The tests for the foundational skills differ from similar tests in academia, in that they specifically probe whether the test taker can apply his skills in a workplace context: e.g., can he read a passage from a technical manual and, from that, figure out what to do next?

The second part of the WorkKeys system is job profiling. To determine the skills needed in a particular job, a trained facilitator works alongside a focus group of workers to first select the tasks most critical to a job, then to identify the skills and skill levels required to enter the job and perform these tasks effectively.

In looking at the STEM jobs that have already been profiled, many require skill scores of 5–6 (on a scale of 1–7), putting them at what would typically be an "early college" level of skill. Most jobs require six to nine different skills.

Table 11.1: Average WorkKeys Skill Scores for Various STEM Jobs; Skill scores are on a scale of 1 to 7[630]

STEM Occupation	Applied Matematics	Locating Information	Reading for Information
Electrical Engineers	5	5	5
Biomedical Engineers	6	5	6
Chemists	6	5	5
Computer and Information Systems	6	5	6
Food Scientists	6	5	5
Actuary	6	5	6
Engineering Managers	7	5	6
Aerospace Engineer	6	5	6

Even the three foundational assessments in Table 11.1 are able to detect, as a first cut, whether someone has the fundamental skills to learn how to become a scientist or engineer. Broadly deployed, they would give us a new tool to identify "STEM-capable" workers, independent of college degree titles or courses taken in high school.

The third part of the skills hiring and credentialing system is closing skills gaps with education and training. After taking the skill assessments, an opportunity exists for persons with skill gaps to learn what it will take to raise their foundational skill levels to gain the certification they need for a particular job. In addition, testing incumbent workers identifies their skill gaps, giving them an opportunity to raise their skills so they can be more successful in the jobs they are in or prepare for advancement into higher-level positions. A gap analysis shows how the person performed relative to the chosen job.

As the WorkKeys system has grown in popularity among educators, employers, and trainers, increasing numbers of organizations are providing training resources linked to the system. Two publishers, KeyTrain and WIN, have developed curricula that address skills gaps. KeyTrain has developed a comprehensive training curriculum with 20,000 pages of interactive materials covering all of the WorkKeys skills. WIN also delivers skill-based training to improve workplace skills with over 1,200 hours and more than 22,000 pages of print and electronic instructional curriculum. With either of these targeted training packages, it takes only 12–15 hours to raise one skill by one level—as opposed to two or more years of formal education (largely because formal education addresses multiple skill areas at once, and therefore takes longer). The cost, via site licenses, is typically less than $10 per user. The fact that one can raise one's skills in far shorter time with far less expense via targeted training means up skilling is within reach of a significant fraction of the population. Some spot shortages we currently see in STEM professions could be addressed far more rapidly in a skills-based hiring system, compared to today's degree-based hiring system.

How far has skills assessment and hiring come since the WorkKeys program was made available? Currently, 40 states offer WorkKeys tests under the umbrella of a state or National Career Readiness Certificate. Certificates are issued to individuals who take the three WorkKeys foundational skills assessments and score at level 3 or above on all three. In addition, several states (Wyoming, Illinois, Kentucky and Michigan) have already legislated the WorkKeys tests be given to all youth in their state, typically alongside the ACT college achievement tests.

the IT sector) or professional societies (in many engineering occupations, especially) or academic testing organizations (ETS, ACT) have built out these tests over years.

None of these tests, alone or in combination, is a substitute for a thorough hiring process. However, an academic degree is also dispensed as a result of satisfactory performance on a series of tests over time; a suite of tests accepted by industry will allow the individual to self-credential at less cost, less time and with more targeted/fine-grained accuracy than re-enrolling in college to obtain another/different/first degree label. The invisible worker becomes visible.

The approach of layering advanced skills tests and content tests on top of the WorkKeys "basic 3" tests to articulate a complete suite of skills and abilities needed for a job is precisely what has been accomplished by the manufacturing sector, through the leadership of the National Association of Manufacturers (NAM), and by the construction industry, through the leadership of the National Center for Construction Education and Research (NCCER). At any level of the profession, it is now possible for the applicant to "test in," with or without a formal degree label. A similar skills pyramid with accompanying tests could be articulated by each industry sector in STEM.

To nationalize skills-based credentialing will require each STEM industry sector to articulate its own skills pyramid, and the accompanying tests—and for employers to retool their hiring processes to require test outcomes of applicants. There are two means by which the federal government can propel this process forward: by incentive and by mandate. In the incentive approach, Congress would appropriate money for one or more federal agencies to hold major grant competitions in which professional societies or trade organizations would be asked to coordinate their industry sector in crafting a skills testing pyramid similar to the NAM example. In addition, the grantee would have to achieve a certain percentage rate of skills-based hiring by their industry sector in order to receive follow-on funding. This latter incentive assures the skills pyramid does not end up being merely a paper exercise.

The mandate approach recognizes that much of our nation's STEM workforce is employed either by government agencies, by contractors funded by the government, or by universities whose research is funded by the government. Thus it is possible to force compliance through budget allocation: agencies/companies/universities receiving government funding would be told that they must skills-test all employees (or all STEM workers); similarly that any hiring they do would have to include a numerical skills profile in the job announcement. This is the less popular unfunded mandate approach, but it is doable. Here, a pilot program would be necessary, not only to expose any unintended consequences, but also to verify that the return on investment to the employer overshadows the initial expense of the unfunded mandate.

Creating A STEM employee reserve for cyclical industries immigration and skills-matching are two ways to fill vacant positions. In times of economic downturn, the reverse approaches work: limit immigration and search less actively for new employees. Cyclical industries face upturns and downturns at intervals that are regular enough that a third option also becomes available: keep existing trained employees in danger of being laid off "in reserve" at universities or government laboratories for a moderate period of time until the industry inevitably comes around again. This approach eliminates STEM jobs temporarily to meet corporate bottom lines, without sacrificing STEM workers. Society benefits, in that it does not have to support the four to six year training costs for new workers to replace the old ones who left because of a six-month-to-one-year business cycle blip.

A furlough grant program could be modeled after a successful program of this kind in the Netherlands. Fearing that if researchers were laid off, companies would not later rehire them, the Dutch government established a program to compensate the wages of private-sector researchers for 18-month fellowships at universities or national laboratories.[633] To qualify for the program, companies had to have experienced a decline in sales and continue to pay

10 percent of the researchers' salary, with the government picking up the remaining 90 percent. The host institution (university or federal lab) had to cover overhead expenses. The Dutch government allocated 180 million Euros and was able to support 2,000 researchers for 18 months.

A similar policy has been implemented by U.S.-based law firms.[634] The firms approached some associates they had promised opportunities to when the market tanked, and offered them the following recommendation: take a marginal salary—a half salary or, in the case of some firms, less than that—to go spend the year doing pro-bono work or working in some other area, but not in the firm.

If it is essential to retain talented STEM professionals, providing some sort of sabbatical is an effective way of accomplishing that goal. Based on the cost of the Dutch program, the United States should allocate up to $100 million (and significantly more in economic downturns) to support private-sector researchers to take 12 to 18 month sabbaticals in universities or federal laboratories. (If the United States were to provide the same amount as the Dutch government on a per-GDP basis, it would have to allocate over $6 billion dollars).

Some of this funding should be available in the form of grants to individuals. Some of it can be made available as tax credits to companies who provide paid educational furloughs to employees. And, in the special case of cyclic defense industries (for whom retention of U.S. citizens is both difficult and necessary) the government could provide funding by rewriting its acquisition guidelines so that government defense contractors are routinely allowed to use existing contract funds to pay for employee education expenses in the event of program termination, or for some period of time after program completion. This would then bridge the most valuable employees over to the next contract while simultaneously updating their STEM skills. Whatever the means, creating a "STEM employee reserve" through some kind of furlough program benefits industry, government and the individual alike: the individual retains a job and updates skills, the company avoids a significant retraining/rehiring burden, and the United States avoids losing its most experienced STEM workers. Most importantly, when a global boomlet begins again, the U.S. companies will have trained people in place, and they will be the first and most able to grab the opportunity.

CHAPTER 12:

Policy Recommendations

This report lays out a blueprint for STEM education that transforms a weak "Some STEM for All" approach into a more powerful, less costly, and more socially equitable "All STEM for Some" approach. Under this approach, STEM educational resources are targeted to those likely to become STEM workers. Crucial to this plan is an aggressive talent identification system that does not rely on chance social networks and accidents of birth, but rather deploys a thorough national recruiting effort aimed at our nation's middle and high schools, much as is done for basketball by the NCAA.

K–12 education, and its accompanying high-stakes tests, should be redirected away from facts, and even concepts, towards skills. Every K–12 student gains the basic skills for a job (the "learn how to learn" skills being prime among these), and perfects those skills in the context of whatever content he or she finds meaningful. Students who pursue STEM additionally obtain skills specific to being a STEM practitioner, such as inquiry and design. In a skills-based paradigm, many of our current distribution requirements melt away. In their place, K–12 students now have the option to perfect core skills by either exploring a single passion in great depth or exploring multiple fields with a far broader range than is possible under a core-requirements-constrained system. In this manner, STEM is enabled to create both the "Deep Divers," and "Interdisciplinary Connectors" industry needs in order to pursue innovation.

In this new paradigm, students can progress as fast as they wish through school, once performance-based credit and funding systems are in place to ensure that neither the student nor the school is penalized for lack of "seat time." These innovations also allow the seamless marriage of virtual and face-to-face education, increasingly a necessity.

Between adjusting the incentives for universities and ensuring that industry engages youth wherever possible in summer jobs and internships, a tighter feedback loop between industry needs and the student's educational path is created.

In recognition of the fact that, at most, 5 percent of the nation's workforce will be STEM workers, not every K–12 student needs to obtain skills specific to STEM professions. Those who do will have a far richer array of resources to choose from: access to virtual classes in STEM topics offered by specialized STEM schools (including boarding schools for those who are less well-off), project-based learning, STEM courses offered in partnership with local community colleges, and more. And, these resources are affordable because they are not mandated for all students, only for those who choose to pursue STEM studies.

In college, this richness continues, but with a twist: STEM students will have more choices and opportunities for interdisciplinary work, and even the chance to start their own companies while still in school, with industry taking a far greater role in the college experience. A major failing of our current workforce system is that while we produce many college graduates with STEM labels, a large fraction of these are unwilling or unable, when they graduate, to take STEM jobs. Between adjusting the incentives for universities (by changing ranking systems and federal grant criteria) and ensuring that industry engages youth wherever possible in summer jobs and internships, a tighter feedback loop between industry needs and the student's educational path is created. Students graduate much more "tuned" to industry needs at every level: B.S., M.S., and Ph.D. Now we can employ a far greater proportion of our domestic STEM graduates, in U.S.-based STEM jobs. And because those individuals have been trained to be superb innovators, as early as in high school, they will create yet more STEM jobs.

Our STEM workforce system has long suffered from an inability to produce the right people, at the right time, in the right numbers to meet industry needs. This redesign of K–12 and higher education will help ensure that we finally have the right mix. Getting the best people into the workforce at the right times, (i.e., synchronizing worker availability with business cycles), is accomplished using national skills-based credentialing, a worker reserve for cyclical industries, and an H-1B visa system whose caps and/or fees float with unemployment rates. And, strategies for increasing STEM graduates at every level—K–12 (through recruiting), B.S. (by eliminating freshman drop-out), M.S. (by meeting the demand for more programs) and Ph.D. (by offering more and better fellowships) would ensure, that however much our STEM worker needs rise as a result of an innovation economy, we will always have enough.

The actions needed to accomplish this vision are organized by the five I's: new educational Institutions; more Incentives to reward institutions for producing more high-quality STEM graduates; more Information to students, parents, and employers to give them more choice and to drive better performance by educational institutions; new systems to capitalize on student Interest; and more Industry involvement. Each recommendation is listed in abbreviated form. At the end of the subject line for each the education level is listed (e.g., K–12, higher education, workforce) and the pages on which the recommendation is more fully discussed are listed.

NEW EDUCATION AND WORKFORCE INSTITUTIONS

The prevailing view in the STEM policy community is that existing institutions can do the job, they just need more: more money, more teachers who are better trained, more information about what works. We disagree. Producing more and better STEM graduates will require new institutions; in particular new specialty science high schools and new kinds of programs and even colleges at the BS level. There is an array of steps that can be taken.

1. **Establish "NewSchools" organizations designed to facilitate the development of new kinds of middle and high schools, including those focused on STEM education. (K–12, p. 86)**
   States should institute a new governance and funding model to support the establishment of more innovative schools, such as STEM schools and schools that focus on project-based learning, along the lines of a proposal brought forward in Minnesota to create a Minnesota's NewSchools organization. NewSchools would be a 501(c)3 non-profit that can raise and direct public, as well as private, resources, to "innovative" schools; that sets binding policy for those schools; and that is responsible for executing directives from the legislative and executive branches, with respect to these schools. In addition, the federal Department of Education should factor whether states have established such organizations in awarding any further Race to the Top grants.

2. **Provide funding to create 400 new STEM-focused high schools. (K–12, p. 84)**
   Congress should allocate $200 million a year for ten years to the Department of Education, to be supplemented by states and local school districts and industry, with the goal of quintupling the number of STEM high schools to 500 and enrollment to around 235,000 by 2015.[635] In addition, institutional partnerships are a key to success of STEM high schools. Whether it's the donation of research equipment, the opening of their facilities to students and faculty, or mentoring of students, technology-based companies can play an important supportive role. To further their involvement, Congress should modify the research and experimentation credit to allow companies to take a flat 30 percent credit for donations of equipment to high schools. Expanding STEM high schools to this extent will make enable slightly more than 1.5 percent of all high schoolers or about one-third of future STEM workers to specialize in STEM.

> Producing more and better STEM graduates will require new institutions; in particular new specialty science high schools and new kinds of programs and even colleges at the BS level.

3. **Create "Early College High Schools" with a STEM track. (K–12, p. 86)**
   Early College High Schools are schools that enable students to also enroll in community college classes during high school. The U.S. Department of Education should partner with the philanthropic foundations currently supporting such programs to incorporate a STEM track within them, or to launch new Early College High School Programs with a STEM focus—particularly in locations where low-income neighborhoods are fortuitously located adjacent to strong STEM colleges and universities.

4. **Foster the expansion of "Dual-Credit" systems. (K–12, p. 86)**
   Dual-credit systems are those in which a high school student may take college courses, typically at a local community college, and receive high school and college credit simultaneously. Expansion of these programs can help more high school students take advanced STEM courses. Via the Elementary and Secondary Education Act, Congress should allocate up to $25 M per year for five years to the Department of Education to encourage the spread of dual-credit systems generally. DOE would release the funding in the form of numerous, but small startup grants to school districts wishing to establish or expand dual-credit courses.

5. **Create an in-person national STEM talent recruiting system. (K–12, p. 115)**
   The United States should move from a weak, potentially expensive, and socially inequitable system of STEM talent self-identification, to a thorough, effective, and more equitable system of directed STEM talent recruiting. Identifying, recruiting, and promoting STEM talent from our nation's high schools should become a systematic national endeavor, similar to NCAA basketball recruiting. A key way to develop this system is to ensure that the hundreds of outreach coordinators managing the hundreds of federal agency high school outreach program sites begin to take on this role. Federal agencies should incentivize such a system by instituting annual reporting requirements on their outreach grants that require grantees to list every high school they have contacted and the names of students they have identified as "promising." In addition, charitable foundations or companies should sponsor the creation of the "America's High School STEM Talent" database to which

the nation's STEM outreach coordinators can report the names and contact information of promising students they encounter. This list then serves as the recruiting resource/mailing list for all scholarship programs, enrichment opportunities, college degrees, and other opportunities offered by any philanthropy, educational institution, nonprofit or company working in STEM. This allows every promising child to be visible and reachable by every effort taking place in the STEM community.

6. **Create a national videogame-based STEM talent recruiting system. (K–12, p. 118)**
   To ensure the widest possible reach of this STEM talent identification program, the federal government, foundations and/or corporations should sponsor the creation of national science videogames, much as the military sponsored the creation of "America's Army" videogame for recruiting purposes. The "high scorers" in these videogames and those who comment intelligently on associated forums could be added to the "America's High School STEM Talent" database. The videogame would serve as both a national teaching tool and a recruiting tool. This can build upon current efforts to use prizes to spur developers to create STEM-based video games, such as the National STEM Video Game Challenge Developer Prize, which challenges emerging and experienced game developers to design mobile games, including games for the mobile web, for young children (grades pre-K through 4) that teach key STEM concepts and foster an interest in STEM subject areas.[636]

7. **Create new kinds of STEM colleges and universities (Higher Education, p. 92)**
   Moving STEM undergraduate and graduate education towards a more interdisciplinary model would not only attract more students to STEM, but also improve the quality of STEM education. For truly transformative change to a more interactive, interdisciplinary model of STEM education, NSF and NIH should allocate grants of up to $10M/year for institutional transformation.

8. **Establish an H-1B Visa commission (Workforce, p. 141)**
   Absent significant expansion of H-1B visas for STEM workers, Congress should establish a commission to manage H-1B visas and instruct it to create an H-1B visa system whose fees (or caps) float with unemployment rate by subfield/occupation. Alternatively, Congress could give the task of deriving an H-1B visa fee (cap) formula to the Department of Labor.

9. **Establish a national skills-based hiring system (Workforce, p. 142)**
   Moving to a more skills-based hiring system would make it easier for workers with STEM skills (but perhaps not with the "right" STEM degrees) to take STEM jobs. To do this Congress should appropriate funds for federal agencies to hold grant competitions in which professional societies or trade organizations would be asked to coordinate their industry sector's move towards skills-based hiring. The grantee would spend one to two years crafting a skills-testing pyramid via engagement with the industry sector in question, ultimately arriving at a consensus skills pyramid. The grantee would have to achieve a certain percentage rate of skills-based hiring by its industry sector in order to receive follow-on funding in subsequent years.

10. **Enable STEM workers to remain working in downturns (Workforce, p. 145)**
    Keeping STEM workers employed during sectoral or national downturns is key to maintaining adequate STEM workers. Toward that end, Congress should establish a furlough program for STEM employees in cyclical industries, whereby such employees could spend up to 18 months at a university or federal laboratory at a one-half to two-thirds pay rate. The funding for this program could come either through direct appropriation, through a tax credit given to industry, or through explicit acquisition contract guidelines that allow flexibility by the contracting company to use acquisition dollars for employee education expenses after project termination or completion.

MORE INCENTIVES TO REWARD INSTITUTIONS FOR PRODUCING MORE HIGH QUALITY STEM GRADUATES

The conventional view of STEM reform is that educational institutions want to do the right thing, they just lack the information. We believe that while more information about what works and what doesn't is helpful, what we really lack are incentives for institutions to adopt these best practices. A wide array of barriers, including institutional inertia, get in the way of real transformative change in educational institutions. Toward that end we make the following recommendations:

11. **Provide prizes to colleges and universities that do best at retaining STEM students (Higher Education, p. 127)**
    STEM degrees could be increased significantly if more freshmen who intended to major in STEM graduated with a STEM degree. Congress should appropriate $66M a year to the National Science Foundation, for five years; this would be matched one to two by a major philanthropy, to be awarded as prizes funds to colleges and universities that have dramatically increased the rate at which their freshmen STEM students graduate with STEM degrees and that can demonstrably sustain that increase over five years. Awards would be offered in three tiers: $5M for small colleges, $10M for mid-size ones and $35M for large universities.

12. **Spur more interdisciplinary STEM teaching and research (Higher Education, p. 92)**
    More undergraduate and graduate interdisciplinary research and teaching would increase both the quality and quantity of STEM graduates. Toward that end, federal agencies should eliminate bias against interdisciplinary work in their grant award criteria. Among other steps, they should include industry representation on review panels at more than a token level.

A wide array of barriers, including institutional inertia, get in the way of real transformative change in educational institutions.

13. **Award prizes for the best STEM departments (Higher Education, p. 76)**
    As described below, the National Survey of Student Engagement (NSSE) provides valuable information on the quality of STEM teaching in college. Philanthropic foundations committed to fostering excellence in STEM education should provide significant prize money for the top three to five NSSE-ranked STEM departments. Through the awarding of prizes, foundations could create a culture where universities strive to top each other in NSSE rankings.

MORE INFORMATION TO DRIVE PERFORMANCE AND CHOICE

When consumers have better information in markets they normally make better decisions, and in so doing put pressure on organizations to provide better goods and services more efficiently. Yet, in so many areas of STEM education, information is lacking. Students, parents and employers are often unaware of how well STEM education institutions are performing. There are variety of steps that can be taken to empower students, parents and employers with more information:

14. **Adopt performance-based assessments of textbooks and other learning materials (K–12, p. 63)**
    State boards of education should either abandon textbook adoption criteria entirely—and leave purchasing decisions to individual schools—or adopt new criteria that apply equally well to all learning media and that speak to skills outcomes rather than topic coverage. Substituting proof that the product improves individual learning outcomes—rather simply covering a long checklist of topics—would stimulate both textbooks and new media to be the best learning tools they can be.

15. **NSF should contract with an organization to establish a national STEM "Test Kitchen" for evaluating teaching methods (K–12 and Higher Education, p. 69)**
    Some kinds of STEM teaching methods have been shown to generate much better learning outcomes than others. But more extensive evaluation of best methods is needed. Toward that end Congress should allocate $5M in construction costs and $2.5M in annual operating costs to NSF for them to contract with an organization to build a showcase "STEM Test Kitchen," perhaps located adjacent to the NSF site in Arlington, VA. The "Test Kitchen" would assess different STEM teaching approaches, side-by-side, and determine which is best suited to delivering a specific concept, as measured by <g> score. The winning "Test Kitchen" teaching approach for each concept would be distributed via popular medium.

16. **Require colleges to report "National Survey of Student Engagement" scores (Higher Education, p. 76)**
    The National Survey of Student Engagement (NSSE), is designed to obtain, on an annual basis, information from more than 1,300 colleges about student participation in programs and activities that those institutions offer for learning and personal development. Unfortunately, few colleges and universities report their institution's scores. To change that, Congress should require that as a "check off" criterion in the certifications and representations section of any

grant proposal that provides student support, universities should have to assert that they have publicly posted their NSSE results. The release of this information will allow parents, teachers, students, funding agencies, and other stakeholders to ascertain that institution's level of student engagement in instructional practices designed to develop Deep Divers and Interdisciplinary Connectors.

17. Develop an industry-ranked list of best STEM departments (Higher Education, p. 101)

Ranking university STEM departments on how well they produce graduates for industry could be a powerful tool for providing incentives for colleges and universities to create programs that are more interdisciplinary and more relevant to industry. Toward that end, an industry-led organization concerned with STEM workforce issues, such as the Industrial Research Institute or the Business-Higher Education Forum, should take on the task of generating the metrics and weights by which academic departments would be evaluated.

18. Develop a "Your Ph.D. is Free" awareness campaign (Higher Education, p. 133)

Ph.D. support mechanisms will have little effect on students' career decisions if students are not aware of these mechanisms. NSF, NASA, DOD, DHS and other agencies that provide Ph.D. fellowships, scholarships and/or assistantships to STEM students should conduct a joint market survey of currently enrolled B.S. students to determine whether students are even aware of these opportunities. If the awareness is low, a marketing plan should be developed to increase awareness (to at least 70 percent of the B.S. STEM student population) of the near-universality of financial support for Ph.D. study.

NEW SYSTEMS TO CAPITALIZE ON STUDENT INTEREST

There is perhaps no more widely held view in the STEM education community than this: we know what students should learn and the best way for America to enhance STEM education is require every student to learn more STEM, regardless of their interests. But an education system, particularly in high school, that ignores the interests of the actual individuals doing the learning is one that is destined not to succeed. We believe that a more effective route to producing the 5 percent or so of workers who have the skills needed to be STEM workers is to embrace a system where student interests and passion for STEM can be realized. This means dramatically reshaping high school education and the direction of education reform through a variety of steps:

19. Shift high schools to skills-based learning (All K–12, p. 64)

Currently, high schools are focused on teaching content (e.g., history, geography, English literature) and not skills (e.g., reading for information, locating information, and applied mathematics). This is reinforced by accountability measures based on content-based tests. Skills-based assessments should replace the NAEP and NCLB subject-matter-based tests for high schoolers. The Department of Education should then develop a plan by which focus on these testable skills would phase in over five years to replace the current subject-area curricular emphasis.

> **... an education system, particularly in high school, that ignores the interests of the actual individuals doing the learning is one that is destined not to succeed.**

20. Develop skills based assessments (K–12 STEM students, p. 67)

For STEM achievement, accountability measures should also move from a content-based to a skills-based paradigm. In lieu of lists of subjects to be taken as standardized STEM curriculum, the outcome of merit should be improved skills scores in inquiry (science), design (engineering), and the understanding and use of symbolic language (mathematics). Suitable tests for these skills should be developed by National Academy of Sciences, National Academy of Engineering, and American Mathematical Society working alongside testing companies such as ETS or ACT. To ensure widespread adoption, federal and state funding for STEM curricula and STEM schools should be tied to the recipient institution's public posting of student scores on these tests, once they are developed.

21. Move high schools to competency-based credit systems (K–12, p. 82)

One way to increase the ability of STEM students to pursue their interests more deeply and to better customize learning would be to allow students to more easily test out of classes. One way to do this would be for Congress to tie ESEA funding to states' adoption of competency-based credit systems. In competency-based credit systems, students receive credit for subject matter learned by taking the end-of-course/end-of-school tests, rather than by spending unneeded seat time in these classes. This option incentivizes student progression through content, opens up time in the curriculum for "in-depth" studies, and helps to retain the brightest high school students, many of whom are bored with the slow pace of seat-time-based instruction.

In concert with competency-based credit, school-district funding authorities should adopt competency-based funding models where funding to schools is granted, not on a seat time/attendance-based formula, but on successful course credit units completed by students. Competency-based funding should be used only in conjunction with meaningful state graduation exams or other enforceable accountability measures (such as NCLB); this avoids the temptation for schools to issue vacuous credits. Done well, competency-based funding allows schools to be rewarded for students' mastery of the material, rather than the number of hours spent in seats. Schools are not penalized if students progress through material faster, learn the material elsewhere, or graduate earlier. Competency-based funding is also an essential component of the successful integration of virtual and physical school systems, along the lines of the Florida Virtual School funding formula model.

22. Increase the freedom of high school students to pursue depth (K–12, p. 78)

In order to provide students the opportunity to pursue depth in their K–12 studies, states should substantially pare the breadth requirements and mandatory course lists required for high school graduation.

Testing a sampling of students on key skills needed, before and after taking specific courses, should indicate the extent to which a course advances a key skill and therefore should be mandated as a graduation requirement. Congress should incentivize the relaxation of science distribution requirements in high schools by tying ESEA funding to the elimination of graduation (or graduation test) criteria in which specific science courses are required by name. Moreover, states should decrease the science courses required for graduation to one, and let that one be of the student's choosing, while reducing math requirements slightly.

23. Increase high school students' access to a wide array of content (K–12, p. 89)

To give students access to courses that are not offered by their own schools, Congress should mandate credit reciprocity across state lines, and between virtual and physical schools, via the Elementary and Secondary Authorization Act. Schools receiving federal funding would have to give their own students graduation credit for courses taken at virtual schools, either in-state or out-of-state, as long as the virtual courses/classes count towards graduation credits in at least one state.

24. Increase the development of online STEM learning tools (K–12, p. 87)

Virtual schools, video games, and other software-based learning can play a key role in boosting STEM education. But more and better tools need to be developed. Congress should allocate $20 million to the National Science Foundation for the development of STEM-related learning tools and products that are intended to be disseminated jointly through the nations' emerging network of virtual schools. Funds would be made available to consortia of virtual schools that apply in partnership with commercial developers of educational products. As an incentive, up to $5M in additional "dissemination" funding for marketing and distribution would be available if the product proves to achieve <g> scores greater than comparable classroom lecture, as measured by NSF's STEM Test Kitchen.

25. Expand undergraduate research opportunities, particularly during freshman year (Higher Education, p. 125)

Because undergraduate research is a highly engaging experience with a track record of greatly diminishing student dropout/switch out from STEM, such experiences should be moved to student's first year of college, as a prophylactic against dropout/switch out endemic to the freshman year. Such a move could increase national B.S. output by as much as 20 percent. To facilitate this transition, the President should issue an Executive Order requesting 30 percent or more of federal-agency-funded undergraduate research experiences be moved to the freshman year and summer following. Prior to the White House issuing the Order, OSTP can be directed to arrive at a list of programs that would be affected by such an order, and asked for process suggestions that would allow for a smooth transition to the new model.

26. Expand interdisciplinary higher education learning (Higher Education, p. 92)

Approximately 75 percent of college students would prefer an interdisciplinary education, and such training is also needed for workforce skills. There are a number of steps that should be taken to expand interdisciplinary learning. Congress should expand the NSF IGERT Program by a factor of three, to $30M annual funding. Where allowed by law, federal agencies should redefine all federally-funded scholarships, fellowships, assistantships, and traineeships such that professors receiving students supported by such mechanisms must include some kind of interdisciplinary training experience for the student.

Alternatively, OSTP can coordinate a multiagency effort to divorce student support from faculty research support. Faculty would apply for research grants as before, but when the grant arrives at the university, it arrives in two parts: a student support portion (tuition and stipend) that is awarded to a student and henceforth travels with the student; and a research support portion (professor salaries, equipment funds, materials, etc.) that stays with the professor. This approach frees students to pursue their own educational interests—which tend to be much more highly interdisciplinary than the narrow in-field research needs of the professor.

27. Spur inclusion of entrepreneurship opportunities for STEM students (Higher Education, p. 106)

Expanding the ability of STEM students to engage in STEM entrepreneurship will not only boost innovation and jobs, it will increase the quality and attractiveness of STEM education. There are a number of steps that should be taken. With federal agency cooperation, universities should define an entrepreneurial leave policy for graduate and students in which students could retain full-time student status for one to two years while launching their own company. In addition, federal agencies supporting university research in STEM should adopt a policy whereby any graduate or post-doctoral student on an assistantship, fellowship, or other form of federal support can petition for a no-cost extension of their assistantship, fellowship, or traineeship, which would allow them to take a "entrepreneurial leave" for one to two years to start a company, and be guaranteed their former student position on their return.

Finally, Congress should make the necessary changes to SBIR authorization to enable students on "entrepreneurial leave" to fund their startups using SBIR monies; individuals who are currently full-time graduate or post-doctoral students would be explicitly eligible for such awards, even if they are foreign nationals, as long as their business is located in the United States. In addition, Congress should work with the Department of Homeland Security to ensure that students who receive SBIR funding (and derive their salaries from that funding) while on official "entrepreneurial leave" are still defined as full-time students, and not company employees, for visa purposes.

MORE INDUSTRY INVOLVEMENT

One reason the education system has not produced the kinds and numbers of STEM graduates needed is that it has attempted to accomplish this task in relative isolation from industry and the world of work. Yet closer links to industry, particularly at the undergraduate and graduate levels, would go a long way toward encouraging more students to major in STEM, to stay in STEM to graduation, and to learn the kinds of skills most needed to power the U.S. innovation economy and keep the United States internationally competitive.

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28. Target a significant share of increases in federal research funding to university programs that partner with industry (Higher Education, p. 109)

Industry-university partnerships not only spur more commercialization and innovation in the economy, they also boost STEM education outcomes. But these partnerships are the exception rather than the rule. To change this, federal agencies should require industry co-funding of many academic research centers, including all the NSF Engineering Research Centers. In addition, Congress should allocate funding for a tripling of NSF's Industry/University Cooperative Research Center (I/UCRC) program, to $21M dollars. NIH should examine the NSF model and propose an equivalent program to Congress.

29. Create an "NSF-Industry Ph.D. Fellows Program" (Higher Education, p. 135)

Increasing linkages with industry for doctoral STEM students can increase the quality of research and education. To increase these linkages Congress should appropriate $21M/year for the establishment of an NSF-Industry Ph.D. Fellows Program, to support an additional 1,000 Ph.D. students in STEM. The new NSF-industry program would work by enabling industry to contribute $20,250 towards each fellowship, in whatever field(s) the company chooses. NSF would match industry funds dollar-for-dollar.

30. Federal grants should routinely require "token cost sharing" from the sector identified as the ultimate customer for the research (Higher Education, p. 97)

One way to expand academic linkages with industry is to require more industry or other organization funding of research. Doing this would broaden the range of inputs during the framing of research projects. Contributions should be small and could be cash or in-kind; the purpose is merely to force up-front communication outside the academic sector. Research projects designed to ultimately yield consumer product or service innovations should have a $5K–$30K cost-sharing requirement with industry; those designed to produce education innovations should have a $1K–$30K cost-sharing requirement from the public or from educational institutions not receiving funds under the grant. Evidence of the origin of the donations would be required.

31. Provide incentives for industry-hosted temporary jobs for undergraduates (Higher Education, p. 138)

Providing more opportunities for college STEM students to work in industry, especially early in their college careers, will help encourage more students to stay in STEM. As a result, the White House should request through executive order that government agencies begin siting some of their student fellowship/internships/co-ops/summer jobs in industry locations (e.g., an agency's industry suppliers or collaborators), if not prohibited by law. At the same time, Congress should allow companies to take a tax deduction for corporate employee time spent mentoring student hires. The company could claim up to 35 percent of the aggregate student hire hours as donations of employee time, at the median prevailing wage of their salaried employees.

ENDNOTES

1. National Science Board, *Science and Engineering Indicators: 2010* (Arlington, VA: National Science Foundation, 2010), http://www.nsf.gov/statistics/seind10/pdf/seind10.pdf.
2. Ibid.
3. Information Technology Industry Council, *Educating the Innovators of Tomorrow: A High-Tech Industry Blueprint* (Washington, DC: Information Technology Industry Council, 2010), http://www.itic.org/clientuploads/EducatingtheInnovatorsofTomorrow_Final.pdf.
4. Daniel Goleman, *Emotional Intelligence* (New York: Bantam Books, 2006).
5. Joy Teague, "Personality Type, Career Preference and Implications for computer Science Recruitment and Teaching," *in Proceedings of the 3rd Australasian conference on Computer science education* (ACSE '98) (New York: ACM, 1998), http://portal.acm.org/beta/citation.cfm?id=289393.289416; Phillip L. Ackerman and Eric D. Heggestad, "Intelligence, Personality, and Interests: Evidence for Overlapping Traits," *Psychological Bulletin* 121, no. 2 (1997): 219–245; Dale R. Baker, "Predictive Value of Attitude, Cognitive Ability, and Personality to Science Achievement in the Middle School," *Journal of Research in Science Teaching* 22, no. 2 (1985): 103–113; Marcel L. Goldschmid, "Prediction of College Majors by Personality Tests," *Journal of Counseling Psychology* 14, no. 4 (1967): 302–308.
6. Scott Andrew Shane, *Born Entrepreneurs, Born Leaders: How Your Genes Affect Your Work Life* (New York: Oxford University Press, 2010).
7. Prasanna Tambe and Lorin M. Hitt, "The Productivity of Information Technology Investments: New Evidence from IT Labor Data," Working Paper, (2010), http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1180722.
8. Robert D. Atkinson and Scott M. Andes, *The Atlantic Century: Benchmarking EU and U.S. Innovation and Competitiveness* (Washington, DC: Information Technology and Innovation Foundation, February 25, 2009), http://www.itif.org/files/2009-atlantic-century.pdf.
9. Romesh Vaitilingam, *UK Industrial Performance Since 1960: Does the Failure of Manufacturing Matter?* (St. Andrews, UK: Royal Economic Society, 1996), http://www.res.org.uk/society/mediabriefings/pdfs/1996/January/deindust.pdf.
10. For a list of other steps that are needed see Robert D. Atkinson, "*An Innovation Economics Agenda for the Next Administration*" Washington, DC: Information Technology and Innovation Foundation, 2008), http://www.itif.org/files/AnInnovationEconomicsAgenda.pdf.
11. Adapted and expanded from: Project Kaleidoscope, *Report on Reports I, 2002* (Washington, DC: Project Kaleidoscope, 2002), http://www.pkal.org/documents/ReportOnReports.cfm; Project Kaleidoscope, *Report on Reports II: Recommendatioins for Urgent Action, 2006* (Washington, DC: Project Kaleidoscope, 2006), http://www.pkal.org/documents/ReportOnReportsII.cfm.
12. Vannevar Bush, Science, *the Endless Frontier: A Report to the President on a Program for Postwar Scientific Research* (Washington, DC: National Science Foundation, 1960).
13. President's Commission on Higher Education, *Higher Education for American Democracy: A Report of The President's Commission on Higher Education* (New York: Harper, 1947).
14. U.S. President's Committee on Education beyond the High School, *Second Report to the President* (Washington, DC, 1957).
15. National Commission on Excellence in Education, *A Nation at Risk: The Imperative for Educational Reform* (Washington, DC, 1983).
16. National Science Board, Task Committee on Undergraduate Science and Engineering Education, *Undergraduate Science, Mathematics and Engineering Education: Role for the National Science Foundation and Recommendations for Action by Other Sectors to Strengthen Collegiate Education and Pursue Excellence in the Next Generation of U.S. Leadership in Science and Technology* (Washington, DC: National Science Foundation, 1986).
17. Sigma Xi, The Scientific Research Society, *An Exploration of the Nature and Quality of Undergraduate Education in Science, Mathematics and Engineering* (New Haven, CT: Sigma Xi, The Scientific Research Society, 1989), http://www.eric.ed.gov/PDFS/ED318634.pdf.
18. Project Kaleidoscope, *What Works: Building Natural Science Communities* (Washington, DC: Project Kaleidoscope, 1991), http://www.pkal.org/documents/VolumeI.cfm.
19. American Association for the Advancement of Science, *Investing in Human Potential: Science and Engineering at the Crossroads* (Washington, DC: AAAS, 1991).
20. Center for Science, Mathematics, and Engineering Education, *From Analysis to Action: Undergraduate Education in Science, Mathematics, Engineering, and Technology* (Washington, DC: National Academies Press, 1996).
21. William J. Clinton and Albert Gore, Jr., *Science in the National Interest* (Washington, DC: Executive Office of the President, Office of Science and Technology, 1994), http://eric.ed.gov/PDFS/ED373994.pdf.
22. Advisory Committee to the Directorate for Education and Human Resources, National Science Foundation, *Shaping the Future: New Expectations for Undergraduate Education in Science, Mathematics, Engineering, and Technology* (Arlington, VA: National Science Foundation, 1996), http://www.nsf.gov/publications/pub_summ.jsp?ods_key=nsf96139.
23. Boyer Commission on Educating Undergraduates in the Research University, *Reinventing Undergraduate Education: A Blueprint for America's Research Universities* (Stony Brook, NY: Boyer Commission, 1998), http://www.eric.ed.gov/PDFS/ED424840.pdf.
24. Government-University-Industry Research Roundtable, *Stresses on Research and Education at Colleges and Universities: Institutional and Sponsoring Agency Responses* (Washington, DC: National Academy of Sciences, 1994), http://www.eric.ed.gov/PDFS/ED376783.pdf.
25. John D. Bransford, Ann L. Brown, and Rodney R. Cocking, eds., *How People Learn: Brain, Mind, Experience, and School* (Washington, DC: National Academies Press, 1999).
26. National Commission on Mathematics and Science, *Before It's Too Late* (Washington, DC: U.S. Department of Education, 2000), http://www2.ed.gov/inits/Math/glenn/report.pdf.
27. National Science and Technology Council, *Ensuring a Strong U.S. Scientific, Technical, and Engineering Workforce in the 21st Century* (Washington, DC: Office of Science and Technology Policy, 2000).

28. Mathematics Learning Study Committee and National Research Council, *Adding It Up: Helping Children Learn Mathematics*, ed. Jeremy Kilpatrick, Jane Swafford, and Bradford Findell (Washington, DC: National Academies Press, 2001).
29. U.S. Commission on National Security/21st Century, *Road Map for National Security: Imperative for Change* (Washington, DC: U.S. Commission on National Security/21st Century, 2001), http://govinfo.library.unt.edu/nssg/PhaseIIIFR.pdf.
30. Business-Higher Education Forum, *Building a Nation of Learners: The Need for Changes in Teaching and Learning To Meet Global Challenges*. (Washington, DC: Business-Higher Education Forum, 2003), http://www.bhef.com/publications/documents/building_nation_03.pdf.
31. Committee on Undergraduate Biology Education to Prepare Research Scientists for the 21st Century and National Research Council, *BIO2010: Transforming Undergraduate Education for Future Research Biologists* (Washington, DC: National Academies Press, 2003).
32. Mary Beth Monroe, Thomas L. O'Kuma, and Warren Hein, *Strategic Programs for Innovations in Undergraduate Physics at Two-year Colleges: Best Practices of Physics Programs* (College Park, MD: American Association of Physics Teachers, 2005), http://www.aapt.org/Programs/projects/spinup/upload/SPIN-UP-TYC-Booklet-2.pdf.
33. Committee on Recognizing, Evaluating, Rewarding, and Developing Excellence in Teaching of Undergraduate Science, Mathematics, Engineering, and Technology, *Evaluating and Improving Undergraduate Teaching in Science, Technology, Engineering, and Mathematics*, ed. Marye Anne Fox and Norman Hackerman (Washington, DC: National Academies Press, 2003).
34. Committee on Challenges for the Chemical Sciences in the 21st Century and Research Council, *Beyond the Molecular Frontier: Challenges for Chemistry and Chemical Engineering* (Washington, DC: National Academies Press, 2003).
35. Committee on Increasing High School Students' Engagement and Motivation to Learn, National Research Council, *Engaging Schools: Fostering High School Students' Motivation to Learn* (Washington, DC: National Academies Press, 2003).
36. William Barker and Mathematical Association of America, *Undergraduate Programs and Courses in the Mathematical Science: CUPM Curriculum Guide 2004* (Washington, DC: Mathematical Association of America, 2004).
37. Building Engineering and Science Talent, *The Talent Imperative: Meeting America's Challenge in Science and Engineering, ASAP* (San Diego, CA: Building Engineering and Science Talent, 2002), http://www.bestworkforce.org/PDFdocs/BESTTalentImperativeFINAL.pdf.
38. Committee on Facilitating Interdisciplinary Research et al., *Facilitating Interdisciplinary Research* (Washington, DC: National Academies Press, 2004).
39. Chris Stephenson, *The New Educational Imperative: Improving High School Computer Science* (New York: Computer Science Teachers Association, 2007), http://www.csta.acm.org/Communications/sub/DocsPresentationFiles/TCEAPres07.pdf.
40. Council on Competitiveness, *National Innovation Initiative Summit and Report: Thriving in a World of Challenge and Change* (Washington, DC: Council on Competitiveness, 2005), http://www.compete.org/images/uploads/File/PDF%20Files/NII_Innovate_America.pdf.
41. Business Roundtable, *Tapping America's Potential: The Education for Innovation Initiative* (Washington, DC: Business Roundtable, 2005), http://www.tap2015.org/about/TAP_report2.pdf.
42. Committee on Science, Engineering, and Public Policy, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future* (Washington, DC: National Academies Press, 2007), http://www.nap.edu/catalog.php?record_id=11463.
43. Shirley M. Malcom et al., *A System of Solutions: Every School, Every Student* (Washington, DC: American Association for the Advancement of Science, 2005).
44. Committee on the Engineer of 2020, Phase II, Committee on Engineering Education, and National Academy of Engineering, *Educating the Engineer of 2020: Adapting Engineering Education to the New Century* (Washington, DC: National Academies Press, 2005).
45. Secretary of Education's Commission on the Future of Higher Education, *A Test of Leadership: Charting the Future of U.S. Higher Education* (Washington, DC: U.S. Department of Education, 2006).
46. Committee on Science Learning, Kindergarten through Eighth Grade and National Research Council, *Taking Science to School: Learning and Teaching Science in Grades K–8*, ed. Richard A. Duschl, Heidi A. Schweingruber, and Andrew W. Shouse (Washington, DC: National Academies Press, 2007).
47. U.S. Department of Education, *Report of the Academic Competitiveness Council* (Washington, DC: U.S. Department of Education, 2007), http://www2.ed.gov/about/inits/ed/competitiveness/acc-mathscience/report.pdf.
48. National Governors Association, I*nnovation America: Building a Science, Technology, Engineering and Math Agenda* (Washington, DC: National Governors Association, 2007), http://www.nga.org/Files/pdf/0702INNOVATIONStem.pdf
49. Achieve, Inc., *Out of Many, One: Toward Rigorous Common Core Standards from the Ground Up* (Washington, DC: Achieve, Inc., 2008), http://www.achieve.org/files/CommonCore.pdf.
50. National Mathematics Advisory Panel, *Foundations for Success: The Final Report of the National Mathematics Advisory Panel* (Washington, DC: U.S. Department of Education, 2008), http://www2.ed.gov/about/bdscomm/list/mathpanel/report/final-report.pdf.
51. National Governors Association, Council of Chief State School Officers, and Achieve, Inc, *Benchmarking for Success: Ensuring U.S. Students Receive a World-Class Education* (Washington, DC: National Governors Association, 2008), http://www.achieve.org/files/BenchmarkingforSuccess.pdf.
52. Committee on Learning Science in Informal Environments, National Research Council, *Learning Science in Informal Environments: People, Places, and Pursuits*, ed. Philip Bell et al. (Washington, DC: National Academies Press, 2009).
53. Commission on Mathematics and Science Education, *The Opportunity Equation: Transforming Mathematics and Science Education for Citizenship and the Global Economy* (New York: Carnegie Corporation of New York; Institute for Advanced Study, 2009), http://opportunityequation.org/uploads/files/oe_report.pdf.
54. National Academy of Engineering and National Research Council, E*ngineering in K–12 Education: Understanding the Status and Improving the Prospects*, ed. Linda Katehi, Greg Pearson, and Michael Feder (Washington, DC: National Academies Press, 2009).

55. Office of Educational Technology, U.S. Department of Education, *Transforming American Education: Learning Powered by Technology* (Washington, DC: U.S. Department of Education, 2010), http://www.ed.gov/sites/default/files/NETP-2010-final-report.pdf.
56. "Ideas in Action with Jim Glassman," *Innovation: Is America Suffery an Innovation Gap*?, July 8, 2010, http://www.ideasinactiontv.com/episodes/2010/07/innovation-is-america-suffering-an-innovation-gap.html.
57. Author's calculations based on data provided in: Dale W. Jorgenson, Mun S. Ho, and Kevin J. Stiroh, "A Retrospective Look at the U.S. Productivity Growth Resurgence," *Federal Reserve Bank of New York Staff Reports*, February 2007, http://www.ny.frb.org/research/staff_reports/sr277.pdf.
58. Elhanan Helpman, *The Mystery of Economic Growth* (Cambridge, MA: Belknap Press of Harvard University Press, 2004).
59. Ibid.
60. Robert D. Atkinson and Andrew S. McKay, *Digital Prosperity: Understanding the Economic Benefits of the Information Technology Revolution* (Washington, DC: Information Technology and Innovation Foundation, 2007), http://www.itif.org/files/digital_prosperity.pdf.
61. Committee on Science, Engineering, and Public Policy, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*.
62. Edwin Mansfield, "Academic Research and Industrial Innovation: An Update of Empirical Findings," *Research Policy* 26, no. 7–8 (1998): 773–776.
63. David T. Coe and Elhanan Helpman, "International R&D Spillovers," *European Economic Review* 39, no. 5 (May 1995): 859–887.
64. Organization for Economic Co-operation and Development, *The OECD Jobs Study: Facts, Analysis, Strategy* (Paris: OECD, 1994), http://www.oecd.org/dataoecd/42/51/1941679.pdf.
65. Organization for Economic Co-operation and Development, *Technology, Productivity and Job Creation: Best Policy Practices* (Paris: OECD, 1998) http://www.oecd.org/dataoecd/39/28/2759012.pdf.
66. Robert D. Atkinson et al., *Innovation Policy on a Budget: Driving Innovation in a Time of Fiscal Constraint* (Washington, DC: Information Technology and Innovation Foundation, 2010), http://www.itif.org/files/2010-innovation-budget.pdf.
67. Organization for Economic Co-operation and Development, *Measuring Innovation: A New Perspective* (Paris: OECD, 2010), http://www.oecd.org/innovation/strategy/measuring.
68. Robert D. Atkinson and Scott M. Andes, *The Atlantic Century: Benchmarking EU and U.S. Innovation and Competitiveness*.
69. National Science Board, *Science and Engineering Indicators: 2010*.
70. For the most part, this report adheres to a discussion of STEM, and resorts to S&E only when STEM-specific data are available.
71. These statistics are tracked by National Science Foundation and the Department of Education.
72. These statistics are tracked primarily by the Department of Labor.
73. A difference to note here is that NSF defines STEM occupations to include science and engineering managers and technicians and technologists but does not include these as S&E occupations. They are instead classified as S&E-related occupations; National Science Board, *Science and Engineering Indicators: 2010*.
74. A difference to note here is that NSF defines STEM occupations to include science and engineering managers and technicians and technologists but does not include these as S&E occupations. They are instead classified as S&E-related occupations. National Science Board, *Science and Engineering Indicators: 2010*.
75. Defense Advanced Research Projects Agency, Information Processing Techniques Office, *Computer Science—Science, Technology, Engineering, and Mathematics (CS-STEM) Education Research Announcement (RA)* (Arlington, VA: DARPA, 2010), www.darpa.mil/IPTO/solicit/baa/RA-10-03_PIP.pdf; Jay Vegso, "Enrollments and Degree Production at US CS Departments Drop Further in 2006–07," *Computing Research News*, March 2008, http://archive.cra.org/CRN/articles/march08/jvegso_enrollments.html and Aerospace Industries Association National Security Council and Industrial Base and Workforce Committee, *Launching the 21st Century American Aerospace Workforce* (Arlington, VA: Aerospace Industries Association, 2008), http://www.aia-aerospace.org/assets/report_workforce_1208.pdf.
76. College Board, *AP Exam National Summary Report: 1997* (New York: College Board, 1998);
    College Board, *AP Exam National Summary Report: 1998* (New York: College Board, 1999);
    College Board, *AP Exam National Summary Report: 1999* (New York: College Board, 2000);
    College Board, *AP Exam National Summary Report: 2000* (New York: College Board, 2001);
    College Board, *AP Exam National Summary Report: 2000* (New York: College Board, 2002);
    College Board, *AP Exam National Summary Report: 2002* (New York: College Board, 2003);
    College Board, *AP Exam National Summary Report: 2003* (New York: College Board, 2004);
    College Board, *AP Exam National Summary Report: 2004* (New York: College Board, 2005);
    College Board, *AP Exam National Summary Report: 2005* (New York: College Board, 2006);
    College Board, *AP Exam National Summary Report: 2006* (New York: College Board, 2007);
    College Board, *AP Exam National Summary Report: 2007* (New York: College Board, 2008);
    College Board, *AP Exam National Summary Report: 2008* (New York: College Board, 2009);
    College Board, *AP Exam National Summary Report: 2009* (New York: College Board, 2010).
77. U.S. Bureau of Labor Statistics, *Occupational Outlook Handbook, 2010–11 Edition*, 2010, http://www.bls.gov/oco/.
78. National Science Board, *Science and Engineering Indicators: 2010*.
79. Ibid.
80. Ibid.
81. Ibid.
82. Ibid.
83. Ibid.
84. Ibid.
85. Ibid.

86. Ibid.
87. Ibid.
88. Ibid.
89. Ibid.
90. For workers, S&E occupations do not include technicians, managers and teachers/professors while STEM does; National Science Board, *Science and Engineering Indicators: 2010*.
91. There are 4.9 million STEM workers. Two percent of this number is 98,000. This would be the typical number of newly created jobs beyond what the educational system provides in terms of degreed students. In 2006, there were approximately 85,000 (65,000 industry + 20,000 academic) H-1B visas approved, very close to the 98,000 education gap.
92. Commission on Professionals in Science and Technology, *The Foreign Born in Science and Technology*, STEM Workforce Data Project (New York: Commission on Professionals in Science and Technology, 2004), https://www.cpst.org/STEM/STEM4_Report.pdf. This appears to be the latest data available from NSF.
93. U.S. Bureau of Labor Statistics, *Occupational Employment Statistics*, 2010, http://www.bls.gov/oes/.
94. U.S. Bureau of Labor Statistics, *Employment Projections*, 2010, http://www.bls.gov/emp/.
95. U.S. Bureau of Labor Statistics, *Occupational Outlook Handbook*, 2010–11 Edition.
96. U.S. Bureau of Labor Statistics, *Employment Projections*.
97. Jobs for the Future, *The STEM Workforce Challenge: the Role of the Public Workforce System in a National Solution for a Competitive Science, Technology, Engineering, and Mathematics (STEM) Workforce* (Washington, DC: U.S. Department of Labor, 2007), www.doleta.gov/youth_services/pdf/STEM_Report_4%2007.pdf; Shirley Ann Jackson, *The Quiet Crisis: Falling Short in Producing American Scientific and Technical Talent* (San Diego, CA: Best, 2003); National Science Board, *The Science and Engineering Workforce: Realizing America's Potential* (Arlington, VA: National Science Foundation, 2003), www.nsf.gov/nsb/documents/2003/nsb0369/nsb0369.pdf; Business Roundtable, *Tapping America's Potential: The Education for Innovation Initiative*.
98. James C. Franklin, "An Overview of BLS Projections to 2016," *Monthly Labor Review* 130, no. 11 (November 2007): 3-12.
99. National Research Council, *Issues Affecting the Future of the U.S. Space Science and Engineering Workforce*.
100. SRI International, *Networking and Information Technology Workforce Study: Final Report* (Arlington, VA: Networking and Information Technology Research and Development Program, 2009), www.nitrd.gov/About/NIT_Workforce_Final_Report_5_29_09.pdf.
101. Larry R. Leslie and Ronald L. Oaxaca, "Scientist and Engineer Supply and Demand," *Higher Education: Handbook of Theory and Research* IX (1993): 154–211; National Research Council, *Forecasting Demand and Supply of Doctoral Scientists and Engineers: Report of a Workshop on Methodology* (Washington, DC: National Academies Press, 2000).
102. Ibid.
103. National Science Board, S*cience and Engineering Indicators: 2010*.
104. Richard B. Freeman, *Investing in the Best and Brightest: Increased Fellowship Support for American Scientists and Engineers* (Washington, DC: Brookings Institution, 2006), http://www.brookings.edu/views/papers/200612freeman.pdf.
105. National Science Board, *Science and Engineering Indicators: 2010*.
106. Commission on Professionals in Science and Technology, *The Foreign Born in Science and Technology*.
107. Information Technology Association of America, *Innovation and a Competitive U.S. Economy: The Case for Doubling the Number of STEM Graduates*, 2005; National Science Board, *An Emerging and Critical Problem of the Science and Engineering Labor Force* (Arlington, VA: National Science Foundation, 2004), http://www.nsf.gov/statistics/nsb0407/nsb0407.pdf.
108. National Science Board, *Science and Engineering Indicators: 2010*; U.S. Citizenship and Immigration Services, *Characteristics of Specialty Occupation Workers* (H-1B): Fiscal Year 2005, Annual Report, 2006.
109. Michael G. Finn, *Stay Rates of Foreign Doctorate Recipients from U.S. Universities, 2007* (Oak Ridge Institute for Science and Education, 2010), http://orise.orau.gov/files/sep/stay-rates-foreign-doctorate-recipients-2007.pdf.
110. Sunil Mithas and Henry C. Lucas, "Are Foreign IT Workers Cheaper? U.S. Visa Policies and Compensation of Information Technology Professionals," *Management Science* 56, no. 5 (May 2010): 745–765.
111. National Science Board, *Science and Engineering Indicators: 2010*.
112. Commission on Professionals in Science and Technology, *The Foreign Born in Science and Technology*.
113. David M. Hart, Zoltan J. Acs, and Spencer L. Tracy Jr., *High-Technology Immigrant Entrepreneurship in the U.S.* (U.S. Small Business Administration, Office of Advocacy, 2009), http://ssrn.com/abstract=1457269.
114. John Haltiwanger, *Entrepreneurship and Job Growth*, 2006, http://ssrn.com/abstract=1244668.
115. Aerospace Industries Association National Security Council and Industrial Base and Workforce Committee, *Launching the 21st Century American Aerospace Workforce*.
116. TopUniversities.com, *World University Rankings* (Quacquarelli Symonds, 2010), www.topuniversities.com/university-rankings/world-university-rankings/home.
117. "U.S. Economy Spurs Foreign Students to Return Home," *University of California*, 2009, http://www.universityofcalifornia.edu/news/article/20785; Annalee Saxenian and Jinn-Yuh Hsu, "The Silicon Valley—Hsinchu Connection: Technical Communities and Industrial Upgrading," *Industrial and Corporate Change* 10, no. 4 (December 2001): 893-920.
118. Pete Engardio, "China's Reverse Brain Drain," *BusinessWeek*, November 19, 2009, http://www.*BusinessWeek*.com/magazine/content/09_48/b4157058821350.htm; Richard C. Paddock, "Booming China Lures Key Professors Home from US," *AOL News*, October 23, 2010, http://www.aolnews.com/world/article/booming-china-lures-science-and-technology-professors-home-from-us/19634851.
119. David Hart, *"Global Flows of Talent: Benchmarking the United States"* (Washington, DC: Information Technology and Innovation Foundation, 2007), http://www.itif.org/files/Hart-GlobalFlowsofTalent.pdf.
120. Robert D. Atkinson and Scott M. Andes, *The Atlantic Century: Benchmarking EU and U.S. Innovation and Competitiveness*.
121. Harold Salzman and B. Lindsay Lowell, *Into the Eye of the Storm: Assessing the Evidence on Science and Engineering Education,*

Quality, and Workforce Demand, 2007, http://ssrn.com/abstract=1034801; Jeffrey J. Kuenzi, *Science, Technology, Engineering, and Mathematics (STEM) Education: Background, Federal Policy, and Legislative Action* (Congressional Research Service, 2008), http://ncseonline.org/NLE/CRSreports/08Apr/RL33434.pdf; National Governors Association, *Innovation America: Building a Science, Technology, Engineering and Math Agenda*; National Commission on Mathematics and Science, Before It's Too Late.

122. Committee on Science, Engineering, and Public Policy, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*.
123. National Center for Education Statistics, "Trends in International Mathematics and Science Study (TIMSS)," 2007, http://nces.ed.gov/timss/index.asp.
124. Organization for Economic Co-operation and Development, *PISA 2006: Science Competencies for Tomorrow's World* (Paris: OECD, 2007), www.oecd.org/document/2/0,3343,en_32252351_32236191_39718850_1_1_1_1,00.html.
125. Ibid.
126. Committee on Science, Engineering, and Public Policy, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future.*
127. Harold Salzman and B. Lindsay Lowell, *Into the Eye of the Storm: Assessing the Evidence on Science and Engineering Education, Quality, and Workforce Demand*.
128. Jeffrey J. Kuenzi, *Science, Technology, Engineering, and Mathematics (STEM) Education: Background, Federal Policy, and Legislative Action*; SRI International, *Networking and Information Technology Workforce Study: Final Report;* Business-Higher Education Forum, *A Commitment to America's Future: Responding to the Crisis in Mathematics and Science Education* (Hagerstown, MD: Business-Higher Education Forum, 2005), www.bhef.com/publications/documents/commitment_future_05.pdf; Fiona Goodchild, "The Pipeline: Still Leaking," *American Scientist*, March 2004, http://www.americanscientist.org/issues/num2/the-pipeline-still-leaking/2; Titus Galama and James R. Hosek, *U.S. Competitiveness in Science and Technology* (Santa Monica, CA: RAND Corp., 2008).
129. Business Roundtable, *Tapping America's Potential: The Education for Innovation Initiative*.
130. Titus Galama and James R. Hosek, *U.S. Competitiveness in Science and Technology.*
131. Robert D. Atkinson and Scott M. Andes, *The Atlantic Century: Benchmarking EU and U.S. Innovation and Competitiveness*.
132. National Science Board, *Science and Engineering Indicators: 2010*.
133. Ibid.
134. Titus Galama and James R. Hosek, *U.S. Competitiveness in Science and Technology.*
135. National Science Board, *Science and Engineering Indicators: 2010*; U.S. Census Bureau, "International Data Base," 2010, www.census.gov/ipc/www/idb/.
136. This definition is significantly broader than the NSF definition of STEM workers and includes medical occupations, managers, and even police detectives.
137. Ibid.
138. Organization for Economic Co-operation and Development, *OECD Science, Technology and Industry Scoreboard 2009* (Paris: OECD, 2009), www.oecd-ilibrary.org/content/book/sti_scoreboard-2009-en.
139. Robert D. Atkinson and Scott M. Andes, *The Atlantic Century: Benchmarking EU and U.S. Innovation and Competitiveness.*
140. National Science Board, *Science and Engineering Indicators: 2010*.
141. Ibid.
142. Christian E. Weller and Holly Wheeler, *Our Nation's Surprising Technology Trade Deficit* (Washington, DC: Center for American Progress, 2008), www.americanprogress.org/issues/2008/03/pdf/high_tech_trade.pdf.
143. Ibid.
144. Robert D. Atkinson and Scott M. Andes, *The Atlantic Century: Benchmarking EU and U.S. Innovation and Competitiveness*.
145. Peter Freeman and William Aspray, *The Supply of Information Technology Workers in the United States* (Washington, DC: Computing Research Association, 1999), http://archive.cra.org/reports/wits/it_worker_shortage_book.pdf; Information Technology Association of America, *Help Wanted: The IT Workforce Gap at the Dawn of a New Century*, 1997; Graham R. Mitchell, *America's New Deficit: The Shortage of Information Technology Workers* (Washington, DC: Office of Technology Policy, 1997).
146. Peter Freeman and William Aspray, *The Supply of Information Technology Workers in the United States*.
147. Bryan Bender, "Alarm over Shortage of Nuclear Experts," *Boston Globe*, April 3, 2010, http://www.boston.com/news/nation/washington/articles/2010/04/03/alarm_over_shortage_of_nuclear_experts/.
148. U.S. Bureau of Labor Statistics, *Labor Force Statistics from the Current Population Survey*, 2010, http://www.bls.gov/cps/.
149. Richard B. Freeman, "A Cobweb Model of the Supply and Starting Salary of New Engineers," *Industrial and Labor Relations Review* 29, no. 2 (January 1976): 236–248.
150. Robert D. Atkinson, *Network Policy and Economic Doctrines* (Washington, DC: Information Technology and Innovation Foundation, 2010), http://www.itif.org/files/2010-network-policy.pdf.
151. Titus Galama and James R. Hosek, *U.S. Competitiveness in Science and Technology*; Richard B. Freeman, "Does Globalization of the Scientific/Engineering Workforce Threaten U.S. Economic Leadership?," *Innovation Policy and the Economy* 6 (2006): 123–157; Michael S. Teitelbaum, "Do We Need More Scientists?," *The Public Interest*, no. 153 (2003): 40–53.
152. Titus Galama and James R. Hosek, *U.S. Competitiveness in Science and Technology.*
153. U.S. Bureau of Labor Statistics, *Labor Force Statistics from the Current Population Survey.*
154. Ibid.
155. Titus Galama and James R. Hosek, *U.S. Competitiveness in Science and Technology.*
156. Katherine G. Abraham, "Structural/Frictional Unemployment vs. Deficient Demand Unemployment: Some New Evidence," *The American Economic Review* 73 (1983): 708–724.
157. Claim made on the basis of examining unemployment rates for registered nurses and licensed practical and vocational nurses

for each July over an 8 year period (2003–present). Prior to 2003, the Census did not collect detailed occupational data. The occupational data were cross-tabulated with employment status using the DataFerrett tool available at http://dataferrett.census.gov/

158. Katharine G. Abraham, "Structural/Frictional vs. Deficient Demand Unemployment: Some New Evidence," *American Economic Review* 73, no. 4 (October 1983): 708–724.
159. National Science Board, *Science and Engineering Indicators: 2010*; U.S. Bureau of Labor Statistics, *Labor Force Statistics from the Current Population Survey*.
160. Harold Salzman and B. Lindsay Lowell, *Into the Eye of the Storm: Assessing the Evidence on Science and Engineering Education, Quality, and Workforce Demand*.
161. U.S. Bureau of Labor Statistics, *Occupational Outlook Handbook, 2010–11 Edition*.
162. Robert D. Atkinson and Scott M. Andes, *The Atlantic Century: Benchmarking EU and U.S. Innovation and Competitiveness*.
163. *Wanted Technologies*, 2010, http://www.wantedtech.com/.
164. National Science Board, *Science and Engineering Indicators: 2010*.
165. Committee on Science, Engineering, and Public Policy, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*; National Science Board, *STEM Education Recommendations for the President-Elect Obama Administration* (Arlington, VA: National Science Foundation, 2009), http://www.nsf.gov/nsb/publications/2009/01_10_stem_rec_obama.pdf; National Science Board, *National Action Plan for Addressing the Critical Needs of the U.S. Science, Technology, Engineering, and Mathematics Education System* (Arlington, VA: National Science Foundation, 2007), http://www.nsf.gov/nsb/documents/2007/stem_action.pdf; U.S. Department of Education, "Preparing Our Children for the Future: Science, Technology, Engineering and Mathematics (STEM) Education in the 2011 Budget," February 1, 2010, http://www.whitehouse.gov/sites/default/files/stem%2011%20final.pdf; Business Roundtable, *Tapping America's Potential: The Education for Innovation Initiative*; Barack H. Obama, "Remarks by the President" (Speech presented at the National Academy of Sciences Annual Meeting, Washington, DC, April 27, 2009), http://www.whitehouse.gov/the_press_office/Remarks-by-the-President-at-the-National-Academy-of-Sciences-Annual-Meeting/; and Jeffrey J. Kuenzi, Christine M. Matthews, and Bonnie F. Mangan, *Science, Technology, Engineering, and Mathematics (STEM) Education Issues and Legislative Options* (Congressional Research Service, 2006), http://ncseonline.org/NLE/CRSreports/06Aug/RL33434.pdf.
166. "Ideas and Commitments from "Sectors of the Village"" (presented at the Convocation on Sustaining Effective Science Education Programs for Grades K–8, Irvine, CA, April 29–30, 2009), http://www.nasonline.org/site/DocServer/Final_reports_from_sectors_of_the_village.pdf.
167. Deborah D. Stine and Christine M. Matthews, *The U.S. Science and Technology Workforce* (Congressional Research Service, 2009), http://fpc.state.gov/documents/organization/128396.pdf.
168. Chris Mooney and Sheril Kirshenbaum, *Unscientific America: How Scientific Illiteracy Threatens Our Future* (New York: Basic Books, 2009).
169. Committee on Science, Engineering, and Public Policy, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*.
170. National Science Board, *Science and Engineering Indicators: 2010*.
171. Ibid.
172. Committee on Science, Engineering, and Public Policy, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*; National Science Board, *National Action Plan for Addressing the Critical Needs of the U.S. Science, Technology, Engineering, and Mathematics Education System*; Business Roundtable, *Tapping America's Potential: The Education for Innovation Initiative*; John P. Holdren and Arne Duncan, "How the U.S. can stay on top," *The Hill*, March 1, 2010, http://thehill.com/special-reports-archive/761-science-a-math-march-2010/84341-how-the-us-can-stay-on-top; National Science Teachers Association, *Legislative Proposals to Strengthen Science and Math Education in the No Child Left Behind Act of 2001* (Arlington, VA: National Science Teachers Association, 2008), http://science.nsta.org/nstaexpress/proposals.pdf; B. Lindsay Lowell et al., *Steady as She Goes? Three Generations of Students through the Science and Engineering Pipeline* (New Brunswick, NJ: John J. Heldrich Center for Workforce Development, 2009), http://policy.rutgers.edu/faculty/salzman/SteadyAsSheGoes.pdf; National Research Council, *Forecasting Demand and Supply of Doctoral Scientists and Engineers: Report of a Workshop on Methodology*; Norman R. Augustine, *Is America Falling Off the Flat Earth?* (Washington, DC: National Academies Press, 2007).
173. Norman R. Augustine, *Is America Falling Off the Flat Earth?*.
174. Ibid.
175. Committee on Science, Engineering, and Public Policy, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*.
176. National Science Board, *National Action Plan for Addressing the Critical Needs of the U.S. Science, Technology, Engineering, and Mathematics Education System*.
177. Elaine Seymour and Nancy M. Hewitt, *Talking About Leaving: Whey Undergraduates Leave the Sciences* (Boulder, CO: Westview Press, 2000).
178. U.S. Bureau of Labor Statistics, *Labor Force Statistics from the Current Population Survey*.
179. Committee on Maximizing the Potential of Women in Academic Science and Engineering et al., *Beyond Bias and Barriers: Fulfulling the Potential of Women in Academic Science and Engineering* (Washington, DC: National Academies Press, 2007).
180. Ibid.
181. Allan Fisher and Jane Margolis, "Unlocking the Clubhouse: the Carnegie Mellon Experience," *Women and Computing* 34, no. 2 (June 2002): 79–83.
182. Ibid.
183. Claudia Goldin and Cecilia Rouse, "Orchestrating Impartiality: The Impact of "Blind" Auditions on Female Musicians," *American Economic Review* 90, no. 4 (October 2000): 715–741.

184. Ibid.
185. Ibid.
186. B. Lindsay Lowell et al., *Steady as She Goes? Three Generations of Students through the Science and Engineering Pipeline*.
187. Norman R. Augustine, *Is America Falling Off the Flat Earth?*
188. National Center for Education Statistics, *Digest of Education Statistics: 2009*, 2010, http://nces.ed.gov/programs/digest/d09/.
189. Ibid.
190. Carlota Perez, "The Double Bubble at the Turn of the Century: Technological Roots and Structural Implications," *Cambridge Journal of Economics* 33, no. 4 (September 2010): 779-805.
191. Committee on Science, Engineering, and Public Policy, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*.
192. Richard B. Freeman, *Investing in the Best and Brightest: Increased Fellowship Support for American Scientists and Engineers*.
193. B. Lindsay Lowell et al., *Steady as She Goes? Three Generations of Students through the Science and Engineering Pipeline*.
194. Committee on Science, Engineering, and Public Policy, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*.
195. National Science Board, *STEM Education Recommendations for the President-Elect Obama Administration*; National Science Board, *National Action Plan for Addressing the Critical Needs of the U.S. Science, Technology, Engineering, and Mathematics Education System*; Barack H. Obama, "Remarks by the President."; John P. Holdren and Arne Duncan, "How the U.S. can stay on top."
196. National Science Board, *National Action Plan for Addressing the Critical Needs of the U.S. Science, Technology, Engineering, and Mathematics Education System*.
197. John P. Holdren and Arne Duncan, "How the U.S. can stay on top."
198. National Science Board, *Science and Engineering Indicators: 2010*.
199. Ibid.
200. Ibid.
201. Organization for Economic Co-operation and Development, *OECD Science, Technology and Industry Outlook 2008*, (Paris: OECD, 2008), http://www.oecd.org/document/36/0,3343,en_2649_34273_41546660_1_1_1_1,00.html.
202. Ibid.
203. High Level Group on Increasing Human Resources for Science and Technology in Europe, *Europe Needs More Scientists* (Brussels: European Commission, 2004), http://ec.europa.eu/research/conferences/2004/sciprof/pdf/final_en.pdf; Jonathan Osborne, Shirley Simon, and Sue Collins, "Attitudes Toward Science: A Review of the Literature and its Implications," *International Journal of Science Education* 25, no. 9 (September 2003): 1049-1079; Ministry of Education, Cutlure, Sports, Science and Technology-Japan, *White Paper on Science and Technology 2008* (*Provisional Translation*) (Tokyo: Ministry of Education, Culture, Sports, Science and Technology-Japan, 2008), http://www.mext.go.jp/english/wp/1260270.htm.
204. High Level Group on Increasing Human Resources for Science and Technology in *Europe, Europe Needs More Scientists*.
205. Jonathan Osborne, Shirley Simon, and Sue Collins, "Attitudes Toward Science: A Review of the Literature and its Implications."
206. Ministry of Education, Culture, Sports, Science and Technology-Japan, *White Paper on Science and Technology 2008* (*Provisional Translation*).
207. National Science Board, *Science and Engineering Indicators: 2010*; Ministry of Education of the People's Republic of China, *The 9th 5-Year Plan for China's Educational Development and the Development Outline by 2010* (Beijing: Ministry of Education of the People's Republic of China, n.d.), http://www.moe.edu.cn/english/planning_n.htm.
208. "National College Entrance Examination of China," *ChinaDetail*, n.d., www.chinadetail.com/History/EducationDevelopmentNationalCollegeEntranceExamination.php.
209. Ibid.
210. Organization for Economic Co-operation and Development, *OECD Science, Technology and Industry Outlook 2008*.
211. National Science Board, *Science and Engineering Indicators: 2010*.
212. U.S. Bureau of Labor Statistics, *Labor Force Statistics from the Current Population Survey*.
213. Dana Markow and Kathleen Moore, "Progress toward power: A follow-up survey of children and parents attitudes about math and science," *National Action Council for Minorities in Engineering Research Letter* 9, no. 1 (2001): 1–8.
214. Ibid.
215. National Science Board, *Science and Engineering Indicators: 2010*; National Science Board, *STEM Education Recommendations for the President-Elect Obama Administration*.
216. Committee on Science, Engineering, and Public Policy, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*.
217. Elizabeth Green, "Building a Better Teacher," *New York Times Magazine*, March 2, 2010, http://www.nytimes.com/2010/03/07/magazine/07Teachers-t.html; Malcolm Gladwell, "Most Likely to Succeed," *New Yorker*, 15, 2008, http://www.newyorker.com/reporting/2008/12/15/081215fa_fact_gladwell; Amanda Ripley, "What Makes a Great Teacher?," *The Atlantic*, January-February 2010, http://www.theatlantic.com/magazine/archive/2010/01/what-makes-a-great-teacher/7841/.
218. Dan Goldhaber, "The Mystery of Good Teaching," *EducationNext 2*, no. 1 (2002): 50–55.
219. Committee on Science, Engineering, and Public Policy, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*.
220. National Science Board, *Science and Engineering Indicators: 2010*.
221. Douglas N. Harris and Tim R. Sass, *Teacher Training, Teacher Quality and Student Achievement* (Washington, DC: National Center for Analysis of Longitudinal Data in Education Research, 2007), http://www.caldercenter.org/pdf/1001059_teacher_training.pdf.
222. Dan D. Goldhaber and Dominic J. Brewer, "Does Teacher Certification Matter? High School Teacher Certification Status and Student Achievement," *Educational Evaluation and Policy Analysis* 22, no. 2 (June 20, 2000): 129–145.

223. U.S. General Accounting Office, *New Directions for Federal Programs to Aid Mathematics and Science Teaching* (Gaithersburg, MD: U.S. General Accounting Office, 1984), http://www.eric.ed.gov/ERICWebPortal/contentdelivery/servlet/ERICServlet?accno=ED241300.
224. David H. Monk, "Subject area preparation of secondary mathematics and science teachers and student achievement," *Economics of Education Review* 13, no. 2 (June 1994): 125–145.
225. Ibid.
226. Data from the 2002 National Educational Longitudinal Study, accessed through the EDAT data tool at http://nces.ed.gov/edat/index.aspx, shows 43.5 percent of K–12 math teachers have bachelor's degrees (or higher) in math, and an additional 16 percent have a minor or second degree in math at the bachelor's level.
227. Dan D. Goldhaber and Dominic J. Brewer, "Does Teacher Certification Matter? High School Teacher Certification Status and Student Achievement."
228. Ibid.
229. National Science Board, *Science and Engineering Indicators: 2010*; Sylvia A. Allegretto, Sean P. Corcoran, and Lawrence R. Mishel, *The Teaching Penalty: Teacher Pay Losing Ground* (Washington, DC: Economic Policy Institute, 2008) .
230. National Science Board, *Science and Engineering Indicators: 2010*; New Teacher Project, *Boosting the Supply and Effectiveness of Washington's STEM Teachers*, January 2010.
231. Business Roundtable, *Tapping America's Potential: The Education for Innovation Initiative*.
232. New Teacher Project, *Boosting the Supply and Effectiveness of Washington's STEM Teachers*.
233. Brian H. Wells, H. Alex Sanchez, and Joanne M. Attridge, *Modeling Student Interest in Science, Technology, Engineering and Mathematics* (Waltham, MA: Raytheon Company, 2007), http://www.raytheon.com/responsibility/rtnwcm/groups/public/documents/content/rtn_stem_whpaper.pdf.
234. Ibid.
235. Eric A. Hanushek et al., *The Market for Teacher Quality*, NBER Working paper Series, 2005, http://ssrn.com/abstract=669453; Eric A. Hanushek and Steven G. Rivkin, "Pay, Working Conditions, and Teacher Quality," *The Future of Children* 17, no. 1 (2007): 69–86.
236. Ibid.
237. Barnett Berry, Alesha Daughtrey, and Alan Wieder, *Teaching Effectiveness and the Conditions that Matter Most in High-Needs Schools: A Policy Brief* (Chapel Hill, NC: Center for Teaching Quality, 2009).
238. National Center for Education Statistics, *Digest of Education Statistics: 2009*.
239. Dire Ballou and Michael Podgursky, "Teacher Recruitment and Retention in Public and Private Schools," *Journal of Policy Analysis and Management* 17, no. 3 (1998): 393–417.
240. Dan Goldhaber, "The Mystery of Good Teaching."
241. "The BHEF U.S. STEM Education Model," *STEM Research and Modeling Network*, 2009, http://stemnetwork.org/model.
242. This assumes that some of the increased pay is returned to the federal government in the form of increased income taxes; Sylvia A. Allegretto, Sean P. Corcoran, and Lawrence R. Mishel, *The Teaching Penalty: Teacher Pay Losing Ground*; National Center for Education Statistics, *Digest of Education Statistics: 2009*.
243. National Science Board, *STEM Education Recommendations for the President-Elect Obama Administration*; "Benchmarks Online," *American Association for the Advancement of Science*, 2009, http://www.project2061.org/publications/bsl/online/index.php.
244. Committee on Science, Engineering, and Public Policy, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*; National Science Board, *National Action Plan for Addressing the Critical Needs of the U.S. Science, Technology, Engineering, and Mathematics Education System*.
245. National Science Board, *STEM Education Recommendations for the President-Elect Obama Administration*.
246. National Science Board, *National Action Plan for Addressing the Critical Needs of the U.S. Science, Technology, Engineering, and Mathematics Education System*.
247. Center for Science, Mathematics, and Engineering Education, *National Science Education Standards* (Washington, DC: National Academies Press, 1996).
248. "Benchmarks Online," *American Association for the Advancement of Science*.
249. Karen S. Hollweg and David Hill, *What is the Influence of the National Science Education Standards?* (Washington, DC: National Academies Press, 2003).
250. Bill Ritter, Jr., *Update on the Common Core State Standards Initiative* (Washington, DC: National Governors Association, 2009), http://edlabor.house.gov/documents/111/pdf/testimony/20091208BillRitterTestimony.pdf; Steven Kussmann, *Common Core State Standards Initiative* (Chantilly, VA: Aligned by Design, 2009), http://www.alignedbydesign.org/Downloads/CommonCoreStateStandardsResearchBrief11-09FINAL.pdf; William H. Schmidt, Richard Houang, and Sharif Shakrani, *International Lessons about National Standards* (Washington, DC: Thomas B. Fordham Institute, 2009), http://bethechangeforkids.org/attachments/088_20090826_International_Lessons_Report.pdf.
251. Bill Ritter, Jr., *Update on the Common Core State Standards Initiative*.
252. Ibid.
253. Ibid.
254. "National Governors Association and State Education Chiefs Launch Common State Academic Standards," *Common Core State Standards Initiative*, n.d., http://www.corestandards.org/articles/8-national-governors-association-and-state-education-chiefs-launch-common-state-academic-standards.
255. "Frequently Asked Questions," *Common Core State Standards Initiative*, n.d., http://www.corestandards.org/frequently-asked-questions.
256. Robert I. Lerman and Arnold Packer, *Will We Ever Learn? What's Wrong With the Common-Standards Project* (Washington, DC: Urban Institute, 2010), http://www.urban.org/url.cfm?ID=901345.

257. Ted Kolderie and Tim McDonald, "How Information Technology Can Enable 21st Century Schools" (Washington, DC: Information Technology and Innovation Foundation, 2009), http://www.itif.org/files/Education_ITIF.pdf.
258. Linda Darling-Hammond, "National Standards and Assessments: Will They Improve Education?," *American Journal of Education* 102, no. 4 (August 1994): 478–510.
259. Ted Kolderie and Tim McDonald, "How Information Technology Can Enable 21st Century Schools."
260. Ethan Yazzie-Mintz, *Charting the Path from Engagement to Acheivement: A Report on the 2009 High School Survey of Student Engagement*.
261. Douglas N. Harris and Tim R. Sass, *Teacher Training, Teacher Quality and Student Achievement.*
262. Elizabeth Green, "Building a Better Teacher."
263. U.S. General Accounting Office, *New Directions for Federal Programs to Aid Mathematics and Science Teaching.*
264. B.D. Rampey, G.S. Dion, and P.L. Donahue, *National Assessment of Educational Progress 2008: Trends in Academic Progress* (Washington, DC: National Center for Education Statistics, 2009).
265. Ibid.
266. Ibid.
267. Diane Ravitch, "Time to Kill 'No Child Left Behind'," *Education Week* 28, 30–36 (2009).
268. Thomas Dee and Brian Jacob, "The Impact of No Child Left Behind on Student Achievement", *NBER* Working paper Series (National Bureau of Economic Research, 2009), http://www.nber.org/papers/w15531.
269. Diane Ravitch, "Time to Kill 'No Child Left Behind'."
270. Annemarie van Langen and Hetty Dekkers, "Cross-National Differences in Participating in Tertiary Science, Technology, Engineering and Mathematics Education," *Comparative Education* 41, no. 3 (August 2005): 329–350; Tim McDonald and Ted Kolderie, "The Role of Information Technology in Creating New Kinds of American High Schools," (Washington, DC: Information Technology and Innovation Foundation, 2009), http://www.itif.org/files/Education_ITIF.pdf.
271. Thomas B. Fordham Institute, *The Mad, Mad World of Textbook Adoption* (Washington, DC: Thomas B. Fordham Institute, 2004), http://www.eric.ed.gov/PDFS/ED485530.pdf.
272. "4x4 Graduation Requirements," *Texas Education Agency*, 2010, http://www.tea.state.tx.us/index2.aspx?id=6108; *Texas Education Code*, 2007–2008, http://ritter.tea.state.tx.us/rules/tac/chapter074/ch074f.html.
273. Ibid.
274. Thomas B. Fordham Institute, *The Mad, Mad World of Textbook Adoption*.
275. Ibid.
276. Center for Education Policy, *State High School Exit Exams: Working to Raise Test Scores* (Washington, DC: Center for Education Policy, 2007), http://www.cep-dc.org/_data/n_0001/resources/live/HSEE2007.pdf.
277. Partnership for 21st Century Skills, *P21 Framework Definitions* (Tucson, AZ: Partnership for 21st Century Skills, 2009), http://www.p21.org/documents/P21_Framework_Definitions.pdf.
278. Jill Casner-Lotto and Mary Wright Benner, *Are They Really Ready to Work?* (USA: Conference Board; Corporate Voices for Working Families; The Partnership for 21st Century Skills; Society for Human Resource Management, 2006), http://www.p21.org/documents/FINAL_REPORT_PDF09-29-06.pdf.
279. Ibid.
280. "Frequently Asked Questions About WorkKeys Skills Tests," ACT, 2010,http://www.act.org/path/parent/tests/workkeys.html.
281. *WorkKeys Occupational Opportunities* (Iowa City, IA: ACT, 2009), http://www.papartners.org/Occupational-Opp-brochure.pdf; "Build a Quality Workforce!," *Job Center of Wisconsin*, 2008, http://www.wisconsinjobcenter.org/ncrc/employer/.
282. Center for Science, Mathematics, and Engineering Education, *National Science Education Standards*.
283. Wikipedia contributors, "Music and mathematics," in *Wikipedia, The Free Encyclopedia*, 2010, http://en.wikipedia.org/wiki/Music_and_mathematics.
284. Randy Elliot Bennett et al., *Problem Solving in Technology-Rich Environments: A Report From the NAEP Technology-Based Assessment Project* (Washington, DC: National Center for Education Statistics, 2007), http://nces.ed.gov/pubsearch/pubsinfo.asp?pubid=2007466.
285. *Science Content Standards for California Public Schools: Kindergarten through Grade Twelve* (Sacramento, CA: California State Board of Education, 2003), www.cde.ca.gov/be/st/ss/documents/sciencestnd.pdf.
286. 15 million is the number of high school students in the United States; see National Center for Education Statistics, *Digest of Education Statistics: 2009*.
287. Ibrahim A. Halloun and David Hestenes, "The Initial Knowledge State of College Physics Students," *American Journal of Physics* 53, no. 11 (1985): 1043–1055; Ibrahim A. Halloun and David Hestenes, "Common Sense Concepts about Motion," *American Journal of Physics* 53, no. 11 (1985): 1056–1065; corrections to the Mechanics Diagnostic test are given in: Ibrahim A. Halloun and David Hestenes, "Modeling Instruction in Mechanics," *American Journal of Physics* 55, no. 5 (1987): 455–462.
288. Julie Libarkin, *Concept Inventories in Higher Education Science* (Washington, DC: National Research Council, 2008), http://www7.nationalacademies.org/bose/Libarkin_CommissionedPaper.pdf.
289. Richard R. Hake, "Interactive-Engagement versus Traditional Methods: A Six-Thousand-Student Survey of Mechanics Test Data for Introductory Physics Courses," *American Journal of Physics* 66, no. 1 (January 1998): 64–74.
290. Ibid.
291. The following section is drawn from an essay by Jane David of the Bay Area Research Group, prepared for ITIF for this report.
292. Ethan Yazzie-Mintz, *Charting the Path from Engagement to Acheivement: A Report on the 2009 High School Survey of Student Engagement* (Bloomington, IN: Center for Evaluation & Education Policy, 2010).
293. Tim McDonald and Ted Kolderie, *The Role of Information Technology in Creating New Kinds of American High Schools.*
294. For example, see the Summer Science Program: http://www.summerscience.org/home/index.php.

295. *Minnesota New Country School*, 2009, http://www.newcountryschool.com.
296. Examples drawn from Core Concepts of Systems Engineering website: http://www.ciese.org.
297. John W. Thomas, *A Review of Research on Project-Based Learning* (San Rafael, CA: Autodesk Foundation, 2000).
298. Jo Boaler, "Alternative Approaches to Teaching, Learning and Assessing Mathematics," *Evaluation and Program Planning* 21, no. 21 (May 1998): 129–141; Jo Boaler, "Learning from Teaching: Exploring the Relationship between Reform Curriculum and Equity," *Journal for Research in Mathematics Education* 33, no. 4 (July 2002): 239–258.
299. Scores represent percent of items correct. Since students in the comprehensive school had no background in specialized technological concepts, their pretest score was close to zero (2 percent) while the comparison group who attended a technological school has some prior knowledge.
300. David Mioduser and Nadav Betzer, "The Contribution of Project-Based-Learning to Higher-Achievers' Acquistion of Technological Knowledge and Skills," *International Journal of Technology and Design Education* 18, no. 1 (2007): 59–77.
301. For example, see Wayne Au, "High-stakes Testing and Curricular Control: A Qualitative Metasynthesis," *Educational Researcher* 36, no. 5 (2007): 258–267; Laura S. Hamilton et al., "Accountability and teaching practices: School-level actions and teacher responses," *Research in the Sociology of Education* 16 (2008): 31–66; Bruce Fuller, Melissa K. Henne, and Emily Hannum, *Strong States, Weak Schools: The Benefits and Dilemmas of Centralized Accountability* (Bingley, UK: Emerald JAI, 2008).
302. Ronald W. Marx et al., "Enacting Project-Based Science," *The Elementary School Journal* 97, no. 4 (March 1997): 341–358.
303. Phyllis C. Blumenfeld et al., "Motivating Project-Based Learning: Sustaining the Doing, Supporting the Learning," *Educational Psychologist* 26, no. 3 (June 1991): 369–398.
304. Ronald W. Marx et al., "Enacting Project-Based Science."
305. Education Sector, *Growing Pains: Scaling Up the Nation's Best Charter Schools* (Washington, DC: Education Sector, 2009), http://www.educationsector.org/publications/growing-pains-scaling-nations-best-charter-schools.
306. Jay Greene and William C. Symonds, "Bill Gates Gets Schooled," *BusinessWeek*, June 26, 2006, http://www.*BusinessWeek*.com/magazine/content/06_26/b3990001.htm.
307. Daniel C. Edelson, Douglas N. Gordin, and Roy D. Pea, "Addressing the Challenges of Inquiry-Based Learning Through Technology and Curriculum Design," *Journal of the Learning Sciences* 8, no. 3 (June 199): 391–450.
308. Amanda Lenhart, Sydney Jones, and Alexandra Macgill, *Adults and Video Games* (Washington, DC: Pew Research Center, 2008).
309. Entertainment Software Association, *Essential Facts about the Computer and Video Game Industry* (Washington, DC: Entertainment Software Association, 2008), http://www.theesa.com/facts/pdfs/ESA_EF_2008.pdf; Amanda Lenhart, Sydney Jones, and Alexandra Macgill, *Adults and Video Games*.
310. Richard R. Hake, "Interactive-Engagement versus Traditional Methods: A Six-Thousand-Student Survey of Mechanics Test Data for Introductory Physics Courses."
311. J.D. Fletcher, *Technology, the Columbus Effect, and the Third Revolution in Learning* (Alexandria, VA: Institute for Defense Analyses, 2001), http://www.eric.ed.gov/PDFS/ED474406.pdf.
312. Merrilea J. Mayo, "Video Games: A Route to Large-Scale STEM Education?," *Science* 323, no. 5910 (January 2009): 79–82.
313. Ibid.
314. Jennifer J. Vogel et al., "Computer Gaming and Interactive Simulations for Learning: A Meta-Analysis," *Journal of Educational Computing Research* 34, no. 3 (2006): 229–243; Richard M. Ryan, C. Scott Rigby, and Andrew Przybylski, "The Motivational Pull of Video Games: A Self-Determination Theory Approach," *Motivation and Emotion* 30, no. 4 (2006): 344–360.
315. Sasha Barab et al., "Making Learning Fun: Quest Atlantis, a Game without Guns," *Educational Technology Research and Development* 53, no. 1 (2005): 86–107; Brett E. Shelton and David A. Wiley, eds., *The Design and Use of Simulation Computer Games in Education* (Rotterdam: Sense Publishers, 2007).
316. Andrew C. Peck and Mark C. Detweiler, "Training Concurrent Multistep Procedural Tasks," *Human Factors* 42, no. 3 (2000): 379–389.
317. Benjamin S. Bloom, ed., *Taxonomy of Educational Objectives: The Classification of Educational Goals* (Chicago: Susan Fauer Company, 1956).
318. Linda J. Sax et al., *The American Freshman: National Norms for Fall 2001* (Los Angeles: Higher Education Research Institute, 2002).
319. David W. Johnson et al., "Effects of Cooperative, Competitive, and Individualistic Goal Structures on Achievement: A Meta-Analysis," *Psychological Bulletin* 89, no. 1 (January 1981): 47–62.
320. See the Games for Learning Institute (G4LI) for more information. This is multi-disciplinary, multi-institutional gaming research alliance to build scientific evidence to support games as learning tools for math and science subjects among middle school students.
321. Brianno D. Coller, *Learning Principles of Mechanical Engineering by Playing Video Games* (DeKalb, IL: Northern Illinois University, 2006), http://www.youtube.com/watch?v=LYGwaI-haOM.
322. Brianno D. Coller and David J. Shernoff, "Video Game-Based Education in Mechanical Engineering: A Look at Student Engagement," *International Journal of Engineering Education* 25, no. 2 (March 2009): 308–317.
323. Brianno D. Coller and Michael J. Scott, "Effectiveness of Using a Video Game to Teach a Course in Mechanical Engineering," *Computers & Education* 53, no. 3 (November 2009): 900–912.
324. *Foldit*, 2010, http://fold.it/portal/.
325. John Bohannon, "Gamers Unravel the Secret Life of Protein," *Wired*, April 20, 2009, http://www.wired.com/medtech/genetics/magazine/17-05/ff_protein.
326. Information Technology Industry Council, *Educating the Innovators of Tomorrow: A High-Tech Industry Blueprint*.
327. Examples of this community's work can be seen at: "[Rogue]: Rupture Formula," *Elitist Jerks*, May 26, 2007, http://elitistjerks.com/f31/t12366-rogue_rupture_formula, which describes how to calculate the damage done by one tick of a specific time-based attack used by rogues. Also see "Discipline Priest Raiding Compendium," *Elitist Jerks*, February 9, 2009, http://elitistjerks.com/f77/

t46027-discipline_priest_raiding_compendium, where different self-made analysts discuss how much energy priests can get back by using a certain spell.

328. Merrilea J. Mayo, "Bringing Game-Based Learning to Scale: The Business Challenges of Serious Games," *International Journal of Learning and Media* (2010), in press.
329. Project Kaleidoscope's agenda can be viewed at http://www.pkal.org.
330. Project Kaleidoscope, *Occasional Paper I: What Works, 1993* (Washington, DC: Project Kaleidoscope, 1993), http://www.pkal.org/documents/ResearchRich.cfm.
331. Project Kaleidoscope's agenda can be viewed at http://www.pkal.org.
332. "Resident Undergraduate Education," *Rensselaer Polytechnic Institute*, 2007, http://www.rpi.edu/president/plan/resident.html.
333. The NSSE survey instruments are available online at http://nsse.iub.edu/html/survey_instruments_2010.cfm.
334. "About NSSE," *National Survey of Student Engagement*, 2010, http://nsse.iub.edu/html/about.cfm.
335. Clayton M. Christensen, Michael B. Horn, and Curtis W. Johnson, *Disrupting Class: How Disruptive Innovation will Change the Way the World Learns* (New York: McGraw-Hill, 2008).
336. National Science Board, *Preparing the Next Generation of STEM Innovators: Identifying and Developing Our Nation's Human Capital* (Arlington, VA: National Science Foundation, 2010), http://www.nsf.gov/nsb/publications/2010/nsb1033.pdf.
337. Gail Russell Chaddock, "US High School Dropout Rate: High, But How High?," *Christian Science Monitor*, June 21, 2006, http://www.csmonitor.com/2006/0621/p03s02-ussc.html.
338. For example, in order to graduate the state of Maryland requires 4 years of English, one year of fine arts, half a year of health education, 4 years of math, 3 years of science (including biology), one year of U.S. history, one year of world history, and one year of government, and one year of technology education, and two years of either language of advanced technical education. This leaves just 2 and ½ courses that the student can choose.
339. The process of disassembly, re-identification of the component parts, and reassembly is nearly identical for all forms of analysis. In a literature class, one would first view a written text as a series of passages, tag and collect all passages in which the author describes the weather, and then write a paper constructed largely from the weather examples to support the hypothesis that the author uses weather metaphors to express human relationships. In geometry class, one first breaks a complex-shaped tract of land into component shapes (squares, triangles, arcs of circles, etc), then calculates the area of each, then adds those back up again to prove that yes, the land occupied by the park is really 10,000 square feet.
340. Jill Casner-Lotto and Mary Wright Benner, *Are They Really Ready to Work?*.
341. Calculations based on data from: U.S. Bureau of Labor Statistics, *Occupational Employment Statistics*; National Science Board, *Science and Engineering Indicators: 2010*.
342. National Academy of Engineering and National Research Council, *Engineering in K–12 Education: Understanding the Status and Improving the Prospects*; E 2 for *Innovation Act*, H.R. 4709, 111th Congress; E 2 for *Innovation Act*, S. 3043, 111th Congress.
343. Hamilton Carter, "Support for the Engineering Education for Innovation Act," *Facebook*, 2010, http://www.facebook.com/group.php?gid=115845055111870, (the bill's Facebook page had three posts as of October 1, 2010, of which two were links to the bill).
344. Chris Stephenson, "Putting Computing in the Core," *Computer Science Teachers Association*, September 4, 2009, http://blog.acm.org/archives/csta/2009/09/advising_govern.html.
345. ACT, *Preparing for the WorkKeys Assessments* (Iowa City, IA: ACT, 2008).
346. Alabama State Department of Education, *Questions and Answers Related to Alabama High School Graduates of the Future* (Montgomery, AL: Alabama State Department of Education, 2008), https://docs.alsde.edu/documents/55/Alabama_High_School_Diploma_Proposal/FAQ_Grad_Options_3_19_08.pdf.
347. Florida Department of Education, *2009-10 Funding for Florida School Districts*, 2009, http://www.fldoe.org/fefp/pdf/fefpdist.pdf.
348. Ibid.
349. Florida TaxWatch Center for Educational Performance and Accountability, *Final Report: A Comprehensive Assessment of Florida Virtual School* (Tallahassee, FL: Florida TaxWatch, 2007).
350. John Watson et al., *Keeping Pace with K–12 Online Learning* (Evergreen, CO: Evergreen Education Group, 2009), http://www.kpk12.com/downloads/KeepingPace09-fullreport.pdf.
351. "WorkKeys Helps At-Risk High School Students Earn a Diploma and Prepare for a Brighter Future," *ACT*, 2010, http://www.act.org/workforce/case/aims.html; Marsha Harmon, "Aims High School Diploma Program, Weld/Larimer County High School Diploma Program," 2010, http://www.southeasternworkkeysconference.com/2008%20Powerpoint%20Presentations/Marsha%20Harmon.ppt.
352. "Magnet Schools Assistance," *U.S. Department of Education*, n.d., http://www2.ed.gov/programs/magnet/index.html.
353. Robert D. Atkinson et al., *Addressing the STEM Challenge by Expanding Specialty Math and Science High Schools* (Washington, DC: Information Technology and Innovation Foundation, 2007), http://www.itif.org/files/STEM.pdf
354. Source for national figures are: U.S. National Center for Education Statistics, *Digest of Education Statistics: 2009*; National Center for Education Statistics, *Baccalaureate and Beyond Longitudinal Study 2000/01* (Washington, DC: U.S. Department of Education, 2003).
355. National data from: "American Community Survey Public Use Microdata Sample 2005," U.S. Census Bureau, 2007, http://factfinder.census.gov/home/en/acs_pums_2005.html.
356. Patrick Rooney et al., *The Condition of Education 2006* (NCES 2006071: U.S. Department of Education, National Center for Education Statistics, 2006), http://nces.ed.gov/pubsearch/pubsinfo.asp?pubid=2006071.
357. Wikipedia contributors, "Specialist school," in *Wikipedia, The Free Encyclopedia*, 2010, http://en.wikipedia.org/wiki/Specialist_school.
358. U.K. Office for Standards in Education, Children's Services and Skills, *Specialist Schools: A Second Evaluation* (London: Ofsted Publications Centre, 2005), http://www.ofsted.gov.uk/content/download/1294/9522/file/Specialist%20schools%20a%20second%20evaluation%20(PDF%20format).pdf.
359. Ibid.

360. David Grant, "Thomas Jefferson High School for Science and Technology: It takes a Corporation to Raise a Great School," *Christian Science Monitor*, December 10, 2009, http://www.csmonitor.com/Business/new-economy/2009/1210/thomas-jefferson-high-school-for-science-and-technology-it-takes-a-corporation-to-raise-a-great-school.
361. "Sponsorship information for mainstream schools," *Specialist Schools and Academies Trust*, 2009, https://www.ssatrust.org.uk/achievement/selfeval/designation/Pages/mainstreamsponsors.aspx.
362. For example, see "NACME - Academy of Engineering," *National Action Council for Minorities in Engineering*, 2009, http://www.nacme.org/NACME_B.aspx?pageid=123.
363. "Thomas Jefferson HS - Demographics," *Fairfax County Public Schools*, 2010, http://schoolprofiles.fcps.edu/schlprfl/f?p=108:13:4120562708065646::::P0_CURRENT_SCHOOL_ID:300; "Fairfax County QuickFacts," *U.S. Census Bureau*, 2010, http://quickfacts.census.gov/qfd/states/51/51059.html.
364. The federal government considers race and Hispanic origin to be two separate and distinct concepts, and thus demographic percentage figures may sum greater than 100 percent.
365. *The SEED School of Washington, D.C.*, n.d., http://www.seedschooldc.org/.
366. *The SEED School of Maryland*, 2009, http://www.seedschoolmd.org/.
367. The President's Council on Science and Technology recently recommended federal support to enable the creation of 200 new STEM high schools. President's Council of Advisors on Science and Technology, *Prepare and Inspire: K–12 Education in Science, Technology, Engineering, and Math (STEM) for America's Future (prepublication version)*, 2010, http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-stemed-report.pdf.
368. Ibid.
369. 15 million is the number of high school students in the United States; see National Center for Education Statistics, *Digest of Education Statistics: 2009*.
370. *Early College High School Initiative*, 2007, http://www.earlycolleges.org/.
371. "Overview & FAQ," *Early College High School Initiative*, 2007, http://www.earlycolleges.org/overview.html.
372. Ibid.
373. Tiffany Waits, J. Carl Setzer, and Laurie Lewis, *Dual Credit and Exam-Based Courses in U.S. Public High Schools: 2002–03* (Washington, DC: National Center for Education Statistics, 2005), http://nces.ed.gov/pubs2005/2005009.pdf.
374. 25 percent Black, 37 percent Latino, 4 percent Asian, 3 percent Native American, 1 percent other/mixed. See Early College High School Initiative, *A Portrait in Numbers* (Boston, MA: Jobs for the Future, 2010), http://www.jff.org/sites/default/files/a_portrait_in_numbers_072110.pdf; Early College High School Initiative, *A Portrait in Numbers*; Marlene B. Seltzer, "Early-College High Schools Beat the Odds," *Education Week*, May 26, 2010, http://www.edweek.org/ew/articles/2010/05/24/33seltzer.h29.html.
375. Melissa Roderick et al., *From High School to the Future: Potholes on the Road to College* (Chicago: Consortium on Chicago School Research at University of Chicago, 2008).
376. Tiffany Waits, J. Carl Setzer, and Laurie Lewis, *Dual Credit and Exam-Based Courses in U.S. Public High Schools: 2002–03*.
377. Ibid.
378. John Watson et al., *Keeping Pace with K–12 Online Learning*.
379. According to Christensen, Horn and Johnson in *Disrupting Class: How Disruptive Innovation will Change the Way the World Learns*, "It is estimated that by 2019, 50 percent of [high school] courses will be delivered online." Their predictions arise from the fact that online enrollment data from 2000-2008 fall on a semi-logarithmic line which, if extended, would cross the 50 percent mark in 2019.
380. *Project Tomorrow*, 2010, http://www.tomorrow.org.
381. The data, facts, and figures in this section were provided by Susan Patrick, President and CEO of iNACOL, the International Association for K–12 Online Learning. However, the opinions and recommendations herein are solely those of ITIF and do not necessarily reflect those of Patrick or iNACOL.
382. J. Carl Setzer and Laurie Lewis, *Distance Education Courses for Public Elementary and Secondary School Students: 2002-03* (Washington, DC: National Center for Education Statistics, 2005), http://nces.ed.gov/pubs2005/2005010.pdf.
383. Anthony G. Picciano and Jeff Seaman, *K–12 Online Learning: A 2008 Follow-up of the Survey of U.S. School District Administrators* (Newburyport, MA: Sloan Consortium, 2009), http://sloanconsortium.org/publications/survey/pdf/k–12_online_learning_2008.pdf.
384. U.S. Department of Education, *Expanding the Advanced Placement Incentive Program* (Washington, DC: U.S. Department of Education, February 2006), http://www2.ed.gov/about/inits/ed/competitiveness/expanding-apip.pdf.
385. *iLabCentral*, 2010, http://ilabcentral.org/ and "Institute for Learning and Brain Sciences (I-LABS)," *University of Washington*, 2010, http://ilabs.washington.edu/.
386. The average of 39 percent is calculated from the following data: FLVS 6th graders performed 32 percent higher, 7th graders 43 percent higher, 8th graders 45 percent higher, 9th graders 49 percent higher and 10th graders, 26 percent higher; Florida TaxWatch Center for Educational Performance and Accountability, *Final Report: A Comprehensive Assessment of Florida Virtual School*.
387. Marsha Lovett, Oded Meyer, and Candace Thille, "The Open Learning Initiative: Measuring the Effectiveness of the OLI Statistics Course in Accelerating Student Learning," *Journal of Interactive Media in Education* (May 2008), http://jime.open.ac.uk/2008/14.
388. Barbara Means et al., *Evaluation of Evidence-Based Practices in Online Learning* (Washington, DC: U.S. Department of Education, 2010), http://www2.ed.gov/rschstat/eval/tech/evidence-based-practices/finalreport.pdf.
389. For example, using webcams to monitor test takers and plagiarism-detection software to scan students' written assignments for undue "borrowing" from web sources.
390. J. Carl Setzer and Laurie Lewis, *Distance Education Courses for Public Elementary and Secondary School Students: 2002-03*.
391. I. Elaine Allen, Jeff Seaman, and Richard Garrett, *Blending In: The Extent and Promise of Blended Education in the United States* (Needham, MA: Sloan Consortium, 2007), http://sloanconsortium.org/publications/survey/pdf/Blending_In.pdf.
392. Charles D. Dziuban, Joel L. Hartman, and Patsy D. Moskal, "Blended Learning," *Educause Research Bulletin*, no. 7 (March 2004),

http://www.educause.edu/ir/library/pdf/ERB0407.pdf.

393. State government, local government, independent school district, or some combination of all three, depending on how school funding responsibility is allocated within the state
394. Florida TaxWatch Center for Educational Performance and Accountability, *Final Report: A Comprehensive Assessment of Florida Virtual School*.
395. Lee Fleming, "Perfecting Cross-Pollination," *Harvard Business Review*, September 2004, http://hbr.org/2004/09/perfecting-cross-pollination/ar/1.
396. Committee on Facilitating Interdisciplinary Research et al., *Facilitating Interdisciplinary Research*; Committee on Undergraduate Biology Education to Prepare Research Scientists for the 21st Century and National Research Council, *BIO2010: Transforming Undergraduate Education for Future Research Biologists*; Committee on Recognizing, Evaluating, Rewarding, and Developing Excellence in Teaching of Undergraduate Science, Mathematics, Engineering, and Technology, *Evaluating and Improving Undergraduate Teaching in Science, Technology, Engineering, and Mathematics*; Committee on the Engineer of 2020, Phase II, Committee on Engineering Education, and National Academy of Engineering, *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*.
397. Committee on Enhancing the Master's Degree in the Natural Sciences and National Research Council, *Science Professionals: Master's Education for a Competitive World* (Washington, DC: National Academies Press, 2008); John Tsapogas, *Recent Engineering and Computer Science Graduates Continue to Earn the Highest Salaries* (Washington, DC: National Science Foundation, 2005), http://www.nsf.gov/statistics/infbrief/nsf06303/nsf06303.pdf.
398. Abt Associates, *Training the Next Generation of Researchers: A Follow-up Study of Students Supported by NSF's Integrative Graduate Education and Research Training Program* (Washington, DC: National Science Foundation, 2010), http://www.abtassociates.com/reports/Abt_1-page_report_summary_May_2010.pdf.
399. Ibid.
400. Diana Rhoten and Stephanie Pfirman, "Women in Interdisciplinary Science: Exploring Preferences and Consequences," *Research Policy* 36, no. 1 (February 2007): 56–75.
401. Committee on Enhancing the Master's Degree in the Natural Sciences and National Research Council, *Science Professionals: Master's Education for a Competitive World*.
402. Evaluation Associates, *Interdisciplinary Research and the Research Assessment Exercise* (London: Evaluation Associates Ltd., 1999). As cited in Diana Rhoten and Stephanie Pfirman, "Women in Interdisciplinary Science: Exploring Preferences and Consequences."
403. Lois Elfman, "Can Interdisciplinarity Attract More Women and Minorities to Academia?," *Diverse: Issues in Higher Education*, November 20, 2007, http://diverseeducation.com/article/10232.
404. National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, *Reshaping the Graduate Education of Scientists and Engineers* (Washington, DC: National Academies Press, 1995).
405. "Mission and History," *Integrative Graduate Education and Research Traineeship*, 2010, http://www.igert.org/public/about/history-and-mission.
406. "Collaborative Research and Training Experience Program," *Natural Sciences and Engineering Research Council of Canada*, 2010, http://www.nserc-crsng.gc.ca/Professors-Professeurs/Grants-Subs/CREATE-FONCER_eng.asp.
407. See "Research Training Groups," *Deutsche Forschungsgemeinschaft*, 2010, http://www.dfg.de/en/research_funding/programmes/coordinated_programmes/research_training_groups/index.html.
408. "Mission and History, *Integrative Graduate Education and Research Traineeship*"; About 20,000 Ph.D.'s/year graduate in STEM disciplines, according to data from the National Science Foundation found at: Division of Science Resources Statistics, National Science Foundation, *Science and Engineering Doctorate Awards: 2005* (Washington, DC: National Science Foundation, 2006), http://www.nsf.gov/statistics/nsf07305/pdf/nsf07305.pdf.
409. "RFA-RM-06-006: Training for a New Interdisciplinary Research Workforce (T90)," *National Institutes of Health*, 2005, http://grants.nih.gov/grants/guide/rfa-files/rfa-rm-06-006.html.
410. National Science Board, *Science and Engineering Indicators: 2010*.
411. Abt Associates, *Training the Next Generation of Researchers: A Follow-up Study of Students Supported by NSF's Integrative Graduate Education and Research Training Program*.
412. NSF is increasingly focused on interdisciplinary research. See "Interdisciplinary Research: Introduction," *National Science Foundation*, 2010, http://www.nsf.gov/od/oia/additional_resources/interdisciplinary_research/.
413. Susan Aud et al., *The Condition of Education 2010* (Washington, DC: National Center for Education Statistics, 2010), http://nces.ed.gov/programs/coe.
414. "Eric Kelderman and Brian O'Leary, "How One University's Revenue Has Evolved," *Chronicle of Higher Education*, June 3, 2010, http://chronicle.com/article/How-One-Universitys-Revenue/65765.
415. National Science Foundation, *Proposal and Award Policies and Procedures Guide* (Arlington, VA: National Science Foundation, 2009), http://www.nsf.gov/pubs/policydocs/pappguide/nsf10_1/nsf10_1.pdf.
416. Derek J. de Solla Price, "Networks of Scientific Papers," Science 149, no. 3683 (1965): 510–515; Susan A. Mohrman and Caroline S. Wagner, *The Dynamics of Knowledge Creation: Phase One Assessment of the Role and Contribution of the Department of Energy's Nanoscale Science Research Centers*, 2008, http://www.marshall.usc.edu/assets/079/16199.pdf.
417. Richard Snodgrass, "Single- versus Double-blind Reviewing: An Analysis of the Literature," *ACM SIGMOD* Record 35, no. 3 (September 2006): 8–21.
418. Peter R. Orszag and John P. Holdren, "Policy on Research Performance Progress Report (RPPR)," April 21, 2010, http://www.nsf.gov/bfa/dias/policy/rppr/policyletter.pdf and *Grants.Gov*, n.d., http://grants.gov.
419. National Science Board, *Investing in the Future: NSF Cost Sharing Policies for a Robust Federal Research Enterprise* (Arlington, VA: National Science Foundation, 2009), http://www.nsf.gov/pubs/2009/nsb0920/nsb0920.pdf.

420. National Science Foundation, *Engineering Research Centers (ERC): Partnerships in Transforming Research, Education and Technology* (Arlington, VA: National Science Foundation, 2009), http://www.nsf.gov/pubs/2009/nsf09545/nsf09545.htm.

421. Tom Henderson, "Punk Mathematics," *Kickstarter,* 2010, http://www.kickstarter.com/projects/1541803748/punk-mathematics. This site may no longer be available after termination of the fundraising for the Punk Mathematics project.

422. A new decennial NRC rankings of doctoral programs is now underway; status updates and relevant publications are available at http://sites.nationalacademies.org/PGA/Resdoc/index.htmp; Committee for the Study of Research-Doctorate Programs in the United States, National Research Council, *Research Doctorate Programs in the United States: Continuity and Change*, ed. Marvin L. Goldberger, Brendan A. Maher, and Pamela Ebert Flattau (Washington, DC: National Academies Press, 1995). This is the most recent published ranking of doctoral programs; "Best Colleges 2010," *U.S. News & World Report*, 2009, http://colleges.usnews.rankingsandreviews.com/best-colleges.

423. This was calculated by using all positive coefficients in Column 5 in Table 5-2a in Ref and normalizing those coefficients to a basis of 100 percentage points. Committee to Assess Research- Doctorate Programs, *A Guide to the Methodology of the National Research Council Assessment of Doctorate Programs*, ed. Jeremiah P. Ostriker et al. (Washington, DC: National Academies Press, 2009).

424. More technically, these are factors that did not receive enough positive votes to generate positive weighting coefficients. (Committee to Assess Research- Doctorate Programs, *A Guide to the Methodology of the National Research Council Assessment of Doctorate Programs*.)

425. Ibid.

426. "How U.S. News Calculates the College Rankings," *U.S. News & World Report*, August 17, 2010, http://www.usnews.com/articles/education/best-colleges/2010/08/17/how-us-news-calculates-the-college-rankings.html.

427. Beckie Supiano, "Olin College Discontinues Policy of Full Scholarships for All," *Chronicle of Higher Education*, June 18, 2009, http://chronicle.com/article/Olin-College-Discontinues/47766/.

428. The description of Olin's unique structure and educational paradigm is drawn in part from information provided by Sherra E. Kerns, F.W. Olin Distinguished Professor of Electrical and Computer Engineering at Olin College, and Stephen Schiffman, Interim Vice President for Academic Affairs and Dean of Faculty at Olin College.

429. "About Olin: Overview," *Franklin W. Olin College of Engineering*, 2010, www.olin.edu/about_olin/overview.aspx.

430. Academically, Olin students rank in the top 1 percent of all high school graduates. Thirteen percent of the Class of 2014 are National Merit Scholars.

431. For example, the Class of 2013 has the following credentials of participation and experience: 87 percent community service; 65 percent competed on academic teams; 60 percent musicians; 69 percent athletes; 5 percent started a company; 45 percent held a job during high school; 24 percent involved in research projects; 27 percent drama/theater; 21 percent worked on student publications; 22 percent participated in student government; 28 percent on a robotics team; 2 Presidential Scholars.

432. "Massachusetts QuickFacts," *U.S. Census Bureau*, 2010, http://quickfacts.census.gov/qfd/states/25000.html.

433. Figure courtesy of Sherra E. Kerns, Franklin W. Olin College of Engineering, 2010.

434. Figure courtesy of Brian Tse, Franklin W. Olin College of Engineering, 2010.

435. "About NNSE," *National Survey of Student Engagement*.

436. Beau Johnson, "Engineering School Rankings" (EngineeringSchools.com, 2006), http://www.engineeringschools.com/engineering-school-rankings.html.

437. "Graduation Rates," *NCHEMS Information Center*, 2009, http://www.higheredinfo.org/dbrowser/index.php?measure=19.

438. Richard K. Miller, Beyond Technology: Preparing Engineering Innovators Who Don't See Boundaries (Needham, MA: Franklin W. Olin College of Engineering, 2010),

439. Ibid.

440. Russell Korte and David Goldberg, "Students as the Key to Unleashing Student Engagement: The Theory, Design, and Launch of a Scalable, Student-Run Learning Community at UIUC" (presented at the ASEE Annual Conference and Exposition, Louisville, KY, June 22, 2010).

441. Vivek Wadhwa et al., *The Anatomy of an Entrepreneur: Family Background and Motivation* (Kansas City, MO: Ewing Marion Kauffman Foundation, 2009), http://www.kauffman.org/uploadedFiles/ResearchAndPolicy/TheStudyOfEntrepreneurship/Anatomy%20of%20Entre%20071309_FINAL.pdf.

442. 44 percent Bachelor's. 30 percent Master's, 14 percent Ph.D./J.D/MD/professional; Vivek Wadhwa et al., *The Anatomy of an Entrepreneur: Family Background and Motivation*; Vivek Wadhwa, Richard Freeman, and Ben Rissing, *Education and Tech Entrepreneurship* (Kansas City, MO: Ewing Marion Kauffman Foundation, 2008), http://www.kauffman.org/uploadedFiles/Education_Tech_Ent_061108.pdf.

443. Ibid.

444. Lara Hulsey, Linda Rosenberg, and Benita Kim, *Seeding Entrepreneurship Across Campus: Early Implementation of the Kauffman Campuses Initiative* (Princeton, NJ: Mathematica Policy Research, 2006), http://www.lorainccc.edu/NR/rdonlyres/7BD9A751-4174-420B-95DA-649173DB9F72/4075/SeedingEntrepreneurshipAcrossCampus.pdf; Adam R. Smith and Dennis Duchon, *Colleges of Business and the Preparation of Entrepreneurs*, 2009, http://www.andersoncei.utk.edu/resources/research/Preparation-of-Entrepreneurs.pdf.

445. Shonika Proctor, "College Entrepreneurship Programs Gaining Recognition in the U.S.," *XChange - The Nightly Business Report Blog*, February 22, 2010, http://www.pbs.org/nbr/blog/2010/02/college_entrepreneurship_progr.html.

446. ABET accreditation criteria can be found at www.abet.org.

447. Undergraduate research projects, as noted in Chapter 9, are marvelous for student retention but are not designed to train students in entrepreneurship.

448. Edward B. Roberts and Charles Eesley, *Entrepreneurial Impact: The Role of MIT* (Kansas City, MO: Ewing Marion Kauffman Foundation, February 2009), http://www.kauffman.org/uploadedFiles/MIT_impact_full_report.pdf.

449. Ibid.
450. Ibid.
451. Ibid.
452. Pilar Mendoza, *Educating for the Public Good through Comprehensive Federal Research and Development Policies*, ASHE/Lumina Policy Briefs and Critical Essays No. 3 (Ames, IA: Iowa State University, Department of Educational Leadership and Policy Studies, 2007), http://www.elps.hs.iastate.edu/documents/ashe/Mendozabrief.pdf.
453. Jennifer Shields Schneider, "A Multivariate Study of Graduate Student Satisfaction and Other Outcomes within Cooperative Research Centers" (Raleigh: North Carolina State University, 2007), http://www.lib.ncsu.edu/resolver/1840.16/52.
454. Ibid.
455. Elizabeth Corley and Monica Gaughan, "Scientists' Participation in University Research Centers: What are the Gender Differences?," *Journal of Technology Transfer* 30 (2005): 371-381.
456. Jennifer Shields Schneider, "A Multivariate Study of Graduate Student Satisfaction and Other Outcomes within Cooperative Research Centers."
457. This was estimated from the 25 startups ("BSAC Inspired Startups," *Berkeley Sensor & Actuator Center*, 2010, http://www-bsac.eecs.berkeley.edu/startups) launched by the Berkeley Sensor and Actuator Center since its founding in 1986 ("About BSAC," *Berkeley Sensor & Actuator Center*, 2010, http://www-bsac.eecs.berkeley.edu/about).
458. FY 2000 saw an I/UCRC budget of 5.2 million (see "Industry/University Cooperative Research Centers: Model Partnerships," *National Science Foundation*, 2008, http://www.nsf.gov/eng/iip/iucrc/directory/overview.jsp); the I/UCRC budget had climbed to 7.85 million by the time of the FY 2010 budget request (see National Science Foundation, *FY 2010 Budget Request to Congress* (Arlington, VA: National Science Foundation, 2009), http://www.nsf.gov/about/budget/fy2010/pdf/entire_fy2010.pdf).
459. ERCs have received roughly $1 billion in total funding over 25 years, implying an annual average level of support at $40 million. See Courtland S. Lewis, *Innovations: ERC-Generated Commercialized Products, Processes, and Startup - 2010* (Arlington, VA: National Science Foundation, February 2010), http://www.erc-assoc.org/topics/policies_studies/ERC%20Innovations%202010-final.pdf; Thomas W. Peterson, "Building an Innovation Ecosystem: The Role of ERCs" (presented at the 2009 ERC Annual Meeting, Bethesda, MD, December 2, 2009), http://www.erc-assoc.org/annmtg/2009_meeting_files/PSI%20Peterson.pdf.
460. The ERC program requires substantial cost-sharing by universities (see National Science Foundation, *Engineering Research Centers (ERC): Partnerships in Transforming Research, Education and Technology*) but no cost-sharing by industry.
461. Teresa R. Berhrens and Denis O. Gray, "Unintended Consequences of Cooperative Research: Impact of Industry Sponsorship on Climate for Academic Freedom and Other Graduate Student Outcomes," *Research Policy* 30, no. 2 (2001): 179–99.
462. Vivek Wadhwa et al., *The Anatomy of an Entrepreneur: Making of a Successful Entrepreneur* (Kansas City, MO: Ewing Marion Kauffman Foundation, 2009), http://www.kauffman.org/uploadedFiles/making-of-a-successful-entrepreneur.pdf.
463. Vivek Wadhwa, Richard Freeman, and Ben Rissing, *Education and Tech Entrepreneurship*.
464. Vivek Wadhwa et al., *The Anatomy of an Entrepreneur: Family Background and Motivation*.
465. Ibid.
466. Edward B. Roberts and Charles Eesley, *Entrepreneurial Impact: The Role of MIT.*
467. Michael G. Finn, *Stay Rates of Foreign Doctorate Recipients from U.S. Universities, 2007*.
468. Edward B. Roberts and Charles Eesley, *Entrepreneurial Impact: The Role of MIT.*
469. An EB-5 visa grants permanent residency to individuals who invest $1M in a U.S. company and create at least 10 jobs; The Startup Visa Act was introduced in the Senate by Senators Kerry and Lugar on Feb 24, 2010 (S. 3029) and in the House by Rep. Maloney on April 29, 2010 (H.R. 5193).
470. "Research and Development," 15 U.S.C. 638, February 1, 2010.
471. Ibid.
472. Estimated from totaling "biology" and "medical/life science" postdocs from Appendix Table #at02–32 in National Science Board, *Science and Engineering Indicators: 2010* and Estimated from "biological sciences" graduate students in Appendix Table #at02-19 in National Science Board, *Science and Engineering Indicators: 2010*.
473. An EB-5 visa grants permanent residency to individuals who invest $1M in a US company and create at least 10 jobs; The *Startup Visa Act* was introduced in the Senate by Senators Kerry and Lugar on Feb 24, 2010 (S. 3029) and in the House by Rep. Maloney on April 29, 2010 (H.R. 5193).
474. "Research and Development," 15 U.S.C. 638, February 1, 2010.
475. Arlene Dohm and Lynn Shniper, "Occupational Employment Projections to 2016," *Monthly Labor Review* 130, no. 11 (November 2007): 86–125.
476. Xianglei Chen, *Students Who Study Science, Technology, Engineering, and Mathematics (STEM) in Postsecondary Education* (Washington, DC: National Center for Education Statistics, 2009), http://nces.ed.gov/pubs2009/2009161.pdf.
477. Paul M. Romer, "Should the Government Subsidize Supply or Demand in the Market for Scientists and Engineers?," *Innovation Policy and the Economy* 1 (2000): 221–252.
478. Commission on Professionals in Science and Technology, *STEM Employment Forecasts and Distributions Among Employment Sectors*, STEM Workforce Data Project (Washington, DC: Commission on Professionals in Science and Technology, 2006), http://www.cpst.org/STEM/STEM7_Report.pdf.
479. "Education Performance Reports FY 2009," *NASA*, 2010, http://www.nasa.gov/offices/education/performance/annualperfreportsfy09.html.
480. Ibid.
481. Ibid.
482. Ibid.
483. Ibid.

484. Ibid.
485. "NCRR Issues 17 Science Education Partnership Awards," *National Center for Research Resources, National Institutes of Health*, 2009, www.ncrr.nih.gov/science_education_partnership_awards/2009/.
486. U.S. Government Accountability Office, *Federal Education Funding: Overview of K–12 and Early Childhood Education Programs* (Washington, DC: U.S. Government Accountability Office, 2010), http://www.gao.gov/new.items/d1051.pdf.
487. National Institute on Drug Abuse, "NOT-DA-10-007: Notice of Availability of Administrative Supplements for R25 Science Education Grants" (National Institutes of Health, 2010), http://grants.nih.gov/grants/guide/notice-files/NOT-DA-10-007.html.
488. U.S. Government Accountability Office, *Federal Education Funding: Overview of K–12 and Early Childhood Education Programs*.
489. "A Guide to Educational Activities," *National Institute of Standards and Technology*, 2010, http://www.nist.gov/public_affairs/edguide.cfm.
490. "NIST Summer Institute for Middle School Science Teachers," *National Institute of Standards and Technology*, 2010, http://www.nist.gov/iaao/summer-institute.cfm.
491. "A Guide to Educational Activities," *National Institute of Standards and Technology*.
492. U.S. Government Accountability Office, *Federal Education Funding: Overview of K–12 and Early Childhood Education Programs*; "Funding - Informal Science Education (ISE)," *National Science Foundation*, 2010, http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5361.
493. U.S. Government Accountability Office, *Federal Education Funding: Overview of K–12 and Early Childhood Education Programs*; "Funding - Innovative Technology Experiences for Students and Teachers," *National Science Foundation*, 2010, http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5467.
494. "Math and Science Partnership (MSP)," *National Science Foundation*, 2010, http://www.nsf.gov/pubs/2010/nsf10556/nsf10556.htm; U.S. Department of Education, "Math and Science Partnership Budgets by State," 2009, http://www.ed-msp.net/public_documents/document/resource/MSP%20Budgets%20by%20State.pdf.
495. Office of Workforce Development for Teachers and Scientists, "U.S. Department of Energy (DOE) National Science Bowl," *U.S. Department of Energy*, 2010, http://www.scied.science.doe.gov/nsb; Office of Science, *Workforce Development for Teachers and Scientists* (Washington, DC: U.S. Department of Energy, 2010), http://www.science.doe.gov/obp/FY_11_Budget/FY%202011%20WDTS%20Cong%20Budget.pdf.
496. Office of Workforce Development for Teachers and Scientists, "ACTS: About," *U.S. Department of Energy*, n.d., http://www.scied.science.doe.gov/scied/ACTS/about.htm; Office of Science, Workforce Development for Teachers and Scientists.
497. *National Defense Education Program*, n.d., http://www.ndep.us; Defense Technical Information Center, "OSD RDT&E Budget Item Justification" (U.S. Department of Defense, February 2008), http://www.dtic.mil/descriptivesum/Y2009/OSD/0601120D8Z.pdf.
498. *National Defense Education Program*, n.d., http://www.ndep.us; Defense Technical Information Center, "OSD RDT&E Budget Item Justification."
499. *Agriculture in the Classroom*, n.d., http://www.agclassroom.org; Jeannie Campbell, "Ag in the Classroom," *Market to Market* (Iowa Public Television, 2009), www.iptv.org/mtom/story.cfm/feature/507.
500. Daniel Terdiman, "'The Sims' Franchise Hits 100 Million Units Sold," *CNET News*, April 16, 2008, http://news.cnet.com/8301-13772_3-9920327-52.html.
501. Merrilea J. Mayo, "Video Games: A Route to Large-Scale STEM Education?"
502. Amanda Lenhart, Sydney Jones, and Alexandra Macgill, *Adults and Video Games*.
503. *WolfQuest*, 2010, http://www.wolfquest.org; David Schaller, Founder and Principal, Eduweb, personal communication, 2009.
504. *Whyville*, 2009, http://www.whyville.net; James Bower, Founder and Chief Visionary Officer, Whyville.net, personal communication, 2009.
505. Ibid.
506. *America's Army*, 2010, http://www.americasarmy.com/.
507. "Playing America's Army," *Frontline* (Arlington, VA: Public Broadcasting Service, June 19, 2009), http://www.pbs.org/wgbh/pages/frontline/digitalnation/waging-war/a-new-generation/playing-americas-army.html.
508. Guinness World Records Limited and Twin Galaxies, *Guinness World Records 2009: Gamer's Edition* (London: Guinness World Records, 2009); "America's Army PC Game Awarded Five Guinness World Records," IGN, February 4, 2009, http://pc.ign.com/articles/951/951008p1.html.
509. "America's Army Wiki," *Software Informer Wiki*, 2010, http://america-s-army.software.informer.com/wiki.
510. David Edery and Ethan Mollick, *Changing the Game: How Video Games are Transforming the Future of Business* (Upper Saddle River, NJ: FT Press, 2009).
511. The data, facts, and figures in this section were provided by Cameron Wilson, Director of Public Policy at ACM. However, the opinions and recommendations herein are solely those of ITIF and do not reflect those of Wilson or ACM.
512. U.S. Bureau of Labor Statistics, *Occupational Employment Statistics*.
513. Commission on Professionals in Science and Technology, *STEM Employment Forecasts and Distributions Among Employment Sectors*.
514. U.S. Bureau of Labor Statistics, *Occupational Employment Statistics*.
515. Total job openings represent the sum of employment increases and net replacements. If employment change is negative, job openings due to growth are zero and total job openings equal net replacements.
516. National Science Foundation, Division of Science Resource Statistics, S&E Degrees: 1996–2006 (Arlington, VA: National Science Foundation, 2008), http://www.nsf.gov/statistics/nsf08321/pdf/nsf08321.pdf; U.S. Bureau of Labor Statistics, *Employment Projections*.
517. CSTA Research Committee, *CSTA National Secondary Computer Science Survey* (2009) (New York: Computer Science Teachers Association, 2009), http://csta.acm.org/Research/sub/Projects/ResearchFiles/CSTASurvey09CSResults_DCarter.pdf.
518. Robert D. Atkinson and Scott M. Andes, *Looking for Jobs?: Look to IT* (Washington, DC: Information Technology and Innovation

Foundation, 2010), http://www.itif.org/files/2010-wm-it-jobs.pdf.

519. In 2008 only 784 African American students nationwide took the AP Computer Science exam. Source: College Board, *AP Exam National Summary Report: 2008* (New York: College Board, 2009), http://www.collegeboard.com/prod_downloads/student/testing/ap/sumrpts/2008/xls/NATIONAL_Summary.xls.
520. In November of 2009 President Obama launched the "Educate to Innovate" campaign, which seeks to improve the participation and performance of America's students in science, technology, engineering, and mathematics (STEM), source: "Educate to Innovate," *White House*, n.d., http://www.whitehouse.gov/issues/education/educate-innovate; In May of 2010, the National Governors Association and the Council of Chief State School Officers released the Common Core Standards Initiative to harmonize mathematics and English Arts education standards. Further, the National Research Council is undertaking an effort to identify and harmonize science standards.
521. Certification programs and requirements for computer science teachers often do not exist and when they do they are typically not connected to actual computer science content knowledge. The organizational confusion around computer science education is contributing to this problem. For example, some courses are placed in the mathematics or science departments, some are within the vocational education departments, and some are within the business departments.
522. This is also known by its original name, the Elementary and Secondary Education Act (ESEA), given when this law was enacted in 1965.
523. While NCLB requires testing of student in science, schools are not held to performance measures in these disciplines. Nevertheless, the practical effect is similar with resources focused on "tested" subjects.
524. "Definitions," 20 U.S.C. 7801, 2010: "The term 'core academic subjects' means English, reading or language arts, mathematics, science, foreign languages, civics and government, economics, arts, history, and geography."
525. In 2008 only 784 African American students nationwide took the AP Computer Science exam. Source: College Board, *AP Exam National Summary Report: 2008*.
526. See *Common Core State Standards Initiative*, 2010, http://corestandards.org.
527. "Conceptual Framework for New Science Education Standards," 2010, http://www7.nationalacademies.org/bose/Standards_Framework_Homepage.html.
528. ACM/CSTA have defined four-part, grade-appropriate set of national K–12 learning standards that underpin the teaching of computer science. See Allen Tucker et al., *A Model Curriculum for K–12 Computer Science: Final Report of the ACM K–12 Task Force Curriculum Committee* (New York: Computer Science Teachers Association, 2006), http://csta.acm.org/Curriculum/sub/CurrFiles/K–12ModelCurr2ndEd.pdf.
529. "SEMATECH Timeline," 2010, http://www.sematech.org/corporate/timeline.htm.
530. Xianglei Chen, *Students Who Study Science, Technology, Engineering, and Mathematics (STEM) in Postsecondary Education*. Tables 4, 6, and 7 were used to generate these data.
531. Data marked * are estimates for all degrees extrapolated from data for B.S. degrees alone. Source is Xianglei Chen, *Students Who Study Science, Technology, Engineering, and Mathematics (STEM) in Postsecondary Education*. Tables 4, 6, and 7 were used to generate these data.
532. Peter A. Daempfle, "An Analysis of the High Attrition Rates among First Year College Science, Math, and Engineering Majors," *Journal of College Student Retention* 5, no. 1 (2003): 37–52.
533. Data for seniors are not shown because the underlying dataset merges data for senior and 5th year students, thereby reporting double-sized cohorts for the terminal year(s) of the study. National Science Board, *Science and Engineering Indicators: 2010*.
534. Ibid.
535. College Board, *How Colleges Organize Themselves to Increase Student Persistence: Four-Year Institutions* (New York: College Board, 2009), http://professionals.collegeboard.com/profdownload/college-retention.pdf.
536. Xianglei Chen and Thomas Weko, *Students Who Study Science, Technology, Engineering, and Mathematics (STEM) in Postsecondary Education*. (NCES 2009-161). Washington, DC: U.S. Department of Education, 2009. Tables 4, 6, and 7 were used to generate these data.
537. Elaine Seymour and Nancy M. Hewitt, *Talking About Leaving: Whey Undergraduates Leave the Sciences*.
538. Ibid.
539. Richard Sabot and John Wakeman-Linn, "Grade Inflation and Course Choice," *Journal of Economic Perspectives* 5, no. 1 (1991): 159–170.
540. Jay H. Parekh, *Do Median Grades Vary Across Departments?*, CHERI Working Paper No. 30 (Ithaca, NY: Cornell University, ILR School, 2002), http://author.ilr.cornell.edu/cheri/workingPapers/upload/cheri_wp30.pdf.
541. These institutions are Amherst College, Duke University, Hamilton College, Haverford College, Pomona College, the University of Michigan, the University of North Carolina and the University of Wisconsin. Richard Sabot and John Wakeman-Linn, "Grade Inflation and Course Choice."
542. Paul M. Romer, "Should the Government Subsidize Supply or Demand in the Market for Scientists and Engineers?."
543. Richard Sabot and John Wakeman-Linn, "Grade Inflation and Course Choice."
544. Elaine Seymour and Nancy M. Hewitt, *Talking About Leaving: Whey Undergraduates Leave the Sciences*.
545. Ibid.
546. Sheila Humphreys and Robert Freeland, *Retention in Engineering: A Study of Freshman Cohorts* (Oakland, CA: Regents of UC, 2002), http://www.eecs.berkeley.edu/~humphrys/retention-eng.pdf.
547. Elaine Seymour and Nancy M. Hewitt, *Talking About Leaving: Whey Undergraduates Leave the Sciences*.
548. James F. McDonough and Bruce A. Harding, "Fostering Creative Thinking in Freshman Engineering," *ASEE Annual Conference Proceedings*, 1996.
549. Ruben Rojas-Oviedo and X. Cathy Qian, "Improving Retention of Undergraduate Students in Engineering through Freshman Courses," *Proceedings of the 2002 American Society for Engineering Education Annual Conference and Exposition*, 2002.

550. Susan H. Russell, *Evaluation of NSF Support for Undergraduate Research Opportunities* (Menlo Park, CA: SRI International, 2006), www.sri.com/policy/csted/reports/university/documents/URO%20Synthesis%20for%20Web.pdf.
551. Ibid.
552. Peter A. Daempfle, "An Analysis of the High Attrition Rates among First Year College Science, Math, and Engineering Majors."
553. Susan H. Russell, *Evaluation of NSF Support for Undergraduate Research Opportunities*.
554. "MU and Division of Biological Sciences Programs," *University of Missouri-Columbia*, 2000, http://www.biology.missouri.edu/diversity/diversityprograms.shtml.
555. http://www.hhmi.org/grants/sea/benefits.html
556. Virginia Wiggins, personal communication. SRC hosts its own undergraduate research programs, placing students in both academic and corporate laboratories.
557. Paul M. Romer, "Should the Government Subsidize Supply or Demand in the Market for Scientists and Engineers?."
558. Carlos Rodriguez, Rita Kirshstein, and Margaret Hale, *Creating and Maintaining Excellence: The Model Institutions for Excellence Program* (Washington, DC: American Institutes for Research, 2005), http://www.air.org/files/MIE_Report_final.pdf.
559. Mark Boroush, *National Patterns of R&D Resources: 2008 Data Update* (Arlington, VA: National Science Foundation, 2010), http://www.nsf.gov/statistics/nsf10314/pdf/nsf10314.pdf; Science and Engineering Degrees: 1950-80. A Source Book. Special Report. Washington, DC: National Science Foundation, 1982. Available at http://www.eric.ed.gov/PDFS/ED222377.pdf; National Science Foundation, Division of Science Resource Statistics, *S&E Degrees: 1966–2006*
560. Mark Baroush, *National Patterns of R&D Resources: 2008 Data Update* (NSF 10-314), Table 5. Arlington, VA: National Science Foundation, 2010. Available at http://www.nsf.gov/statistics/nsf10314/tables/tab5.xls; Felix H. Lindsay and Charles H. Dickens, *Science and Engineering Degrees: 1950-80. A Source Book. Special Report*. (Washington, DC: National Science Foundation, 1982), http://www.eric.ed.gov/PDFS/ED222377.pdf; and National Science Foundation, Division of Science Resource Statistics, *S&E Degrees: 1966–2006*.
561. National Institutes of Health, Office of Communications and Public Liaison, Online Information Branch, *The NIH Almanac*, 2009, http://www.nih.gov/about/almanac/index.html; Mark Boroush, *National Patterns of R&D Resources: 2008 Data Update*; Felix H. Lindsay and Charles H. Dickens, *Science and Engineering Degrees: 1950–80. A Source Book. Special Report*; National Science Foundation, Division of Science Resource Statistics, *S&E Degrees: 1966–2006*.
562. Merrilea J. Mayo, David Bruggeman, and John F. Sargent, *Correlation between Federal R&D Expenditures in the Math, Physical Sicence and Engineering Disciplines*, 2002.
563. Committee on Enhancing the Master's Degree in the Natural Sciences and National Research Council, *Science Professionals: Master's Education for a Competitive World*.
564. National Science Foundation, Division of Science Resource Statistics, Median Annual Salary of U.S. Scientists and Engineers, by Field and Highest Level and Degree: 1993, 1999, 2006. http://www.nsf.gov/statistics/sestat/
565. National Science Foundation, Division of Science Resource Statistics, *Characteristics of Recent Science and Engineering Graduates: 2006* (Arlington, VA: National Science Foundation, 2010), www.nsf.gov/statistics/nsf10318/pdf/nsf10318.pdf; National Science Foundation, Division of Science Resource Statistics, *Characteristics of Doctoral Scientists and Engineers in the United States: 2006* (Arlington, VA: National Science Foundation, 2009), www.nsf.gov/statistics/nsf09317/pdf/nsf09317.pdf.
566. "PSM Overview," *Professional Science Master's*, 2010, www.sciencemaster's.com/PSMOverview/tabid/57/Default.aspx.
567. "Award Search - Awardee Information," *National Science Foundation*, 2008, http://www.nsf.gov/awardsearch/.
568. Committee on Enhancing the Master's Degree in the Natural Sciences and National Research Council, *Science Professionals: Master's Education for a Competitive World*.
569. Ibid.
570. Council of Graduate Schools, *Professional Science Master's Degree: Background and Overview*, 2010, www.sciencemaster's.com/portals/0/powerpoints/PSM_employer_PPT.ppt; National Science Foundation, Division of Science Resource Statistics, *Graduate Students and Postdoctorates in Science and Engineering: Fall 2007* (Arlington, VA: National Science Foundation, 2010), www.nsf.gov/statistics/nsf10307/pdf/nsf10307.pdf; "Women, Minorities, and Persons with Disabilities in Science and Engineering: Figure D-2—US National Science Foundation (NSF)," *National Science Foundation*, 2008, http://www.nsf.gov/statistics/wmpd/figd-2.htm.
571. "PSM Overview," *Professional Science Master's*.
572. Most companies launching a new product would spend 2–7 percent of their budget on advertising; a similar calculation can be used to estimate what level of advertising is needed for employers to "buy" the Sloan and Keck products, their PSM graduates. In this case, the base for the calculation would be the number of such graduates each year times their expected annual salary. This is the product employers are buying, and the cost at which they are buying it.
573. Richard B. Freeman, *Investing in the Best and Brightest: Increased Fellowship Support for American Scientists and Engineers*.
574. Committee on Science, Engineering, and Public Policy, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*.
575. Pamela Ebert Flattau, et al., *The National Defense Education Act of 1958: Selected Outcomes* (Washington, DC: Insitute for Defense Analyses, Science & Technology Policy Institute, 2006), https://www.ida.org/stpi/pages/D3306-FINAL.pdf.
576. Ibid.
577. Ibid.
578. Ibid.
579. Committee on Science, Engineering, and Public Policy, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*.
580. Richard B. Freeman, *Investing in the Best and Brightest: Increased Fellowship Support for American Scientists and Engineers*.
581. Richard Freeman, "Investing in the Best and the Brightest: Increased Fellowship Support for American Scientists and Engineers," The Brookings Institute, 2006, http://www.brookings.edu/views/papers/200612freeman.pdf.

582. U.S. Department of Education, "Preparing Our Children for the Future: Science, Technology, Engineering and Mathematics (STEM) Education in the 2011 Budget."

583. Richard B. Freeman, *Investing in the Best and Brightest: Increased Fellowship Support for American Scientists and Engineers*.

584. These figures come from data that encompass all S&E graduate students, including social scientists. National Science Board, *Science and Engineering Indicators: 2010*.

585. Ibid.

586. National Science Foundation, Division of Science Resource Statistics, *Federal Science and Engineering Support to Universities, Colleges, and Nonprofit Institutions: FY 2007* (Arlington, VA: National Science Foundation, 2009), http://www.nsf.gov/statistics/nsf09315/pdf/nsf09315.pdf.

587. "Graduate Research Fellowship Program (GRFP)," *National Science Foundation*, 2005, http://www.nsf.gov/pubs/2005/nsf05601/nsf05601.htm; "NOT-OD-10-047: Ruth L. Kirschstein National Research Service Award (NRSA) Stipends, Tuition/Fees and Other Budgetary Levels Effective for Fiscal Year 2010," *National Institutes of Health*, 2010, http://grants2.nih.gov/grants/guide/notice-files/NOT-OD-10-047.html; "NDSEG - National Defense Science and Engineering Graduate Fellowship," *American Society for Engineering Education*, n.d., http://ndseg.asee.org/about_ndseg/stipends_and_allowances.

588. Wendy Chao, "2009-10 Best Graduate Student Stipends," *Wendy Chao*, 2010, http://www.wendychao.com/science/stipends/2009-10.html.

589. "Best Graduate Schools," *U.S. News & World Report*, 2009, http://grad-schools.usnews.rankingsandreviews.com/best-graduate-schools.

590. Wendy Chao, "2009–10 Best Graduate Student Stipends."

591. Sharon S. Goldsmith, Jennifer B. Presley, and Elizabeth A. Cooley, *National Science Foundation Graduate Research Fellowship Program: Final Evaluation Report* (Arlington, VA: National Science Foundation, 2002), http://www.nsf.gov/pubs/2002/nsf02080/nsf02080.pdf.

592. Ibid.

593. Ibid.

594. Ibid.

595. Paul Romer. Should the Government Subsidize Supply or Demand in the Market for Scientists and Engineers?

596. Ashok Bardhan, Daniel L. Hicks, and Dwight Jaffee, *How Responsive is Higher Education? The Linkages between Education and the Labor Market* (Berkeley, CA: UC Berkeley, Fisher Center for Real Estate and Urban Economics, 2010), http://escholarship.org/uc/item/6b1889dc.

597. Associated Press, "Defense Industry Facing Shortage of Workers," *msnbc.com*, March 4, 2008, http://www.msnbc.msn.com/id/23469399/.

598. Job listings for this specialty can be found at http://www.quantfinancejobs.com/. The academic requirements vary but "PhD from a well-regarded university, in Physics, Computer Science, Machine Learning, Signal Processing, Computer Vision, Statistics, Econometrics, Operations Research" is not atypical. The starting salary for the position just quoted was $250K/year, for a junior quantitative analyst working in an investment bank in New York City. Another $250K/year job asks for "Bachelors, Master's or PhD in Computer Science etc from a red brick University with a high GPA." Clearly, these ads are looking for a rare skill set, that no particular university or degree captures well—because the label requirements are so vague (BS, MS or PhD, one of any number of fields, any decent university).

599. Established in the early years of NSF, the program provides the nation's most promising graduate students with great flexibility in selecting the university of their choice and gives them the intellectual independence to follow their research ideas unfettered by the exigencies of mode of support.

600. Moreover, research suggests that there is little difference in ethical behavior by faculty whether they are funded by industry or government; see Brian C. Martinson et al., "Institutions' Expectations for Researchers' Self-Funding, Federal Grant Holding, and Private Industry Involvement: Manifold Drivers of Self-Interest and Researcher Behavior," *Academic Medicine* 84, no. 11 (2009): 1491–1499.

601. Denis O. Gray and S. George Walters, *Managing the Industry/University Cooperative Research Center* (Columbus, OH: Battelle Press, 1998), http://www.ncsu.edu/iucrc/PDFs/PurpleBook/FrontSection.pdf.

602. Donald H. Wulff, et al., "The Development of Graduate Students as Teaching Scholars: A Four-Year Longitudinal Study," in *Paths to the Professoriate: Strategies for Enriching the Preparation of Future Faculty* (San Francisco: Jossey-Bass, 2004); Chris M. Golde and Timothy M. Dore, *At Cross Purposes: What the Experiences of Today's Doctoral Students Reveal about Doctoral Education* (Philadelphia, PA: Pew Charitable Trusts, 2001), http://www.phd-survey.org/report%20final.pdf; Jody D. Nyquist and Bettina J. Woodford, "Re-envisioning the Ph.D.: A Challenge for the Twenty-First Century," in *Paths to the Professoriate: Strategies for Enriching the Preparation of Future Faculty* (San Francisco: Jossey-Bass, 2004) .

603. Chris M. Golde and Timothy M. Dore, *At Cross Purposes: What the Experiences of Today's Doctoral Students Reveal about Doctoral Education*.

604. Stephen P. Campbell, Angela K. Fuller, and David A.G. Patrick, "Looking Beyond Research in Doctoral Education," *Frontiers in Ecology and the Environment* 3, no. 3 (2005): 153–160.

605. "DHS Scholarship Program," *Oak Ridge Associated Universities*, n.d., http://www.orau.gov/dhsed; "NSF Scholarships in Science, Technology, Engineering, and Mathematics," *National Science Foundation*, 2010, http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5257; "SMART - Science, Mathematics & Research for Transformation - Part of the National Defense Education Program," *American Society for Engineering Education*, 2010, http://smart.asee.org/about, (this scholarship originates from DOD funds but is administered by the American Society for Engineering Education and the Naval Postgraduate School); "Undergraduate Scholarship Program - Training Programs in the Biomedical Sciences - Office of Intramural Training & Education at the National Institutes of Health," *National Institutes of Health*, n.d., https://www.training.nih.gov/programs/ugsp.

606. "Undergraduate Scholarships," *American Institute of Aeronautics and Astronautics*, 2010, http://www.aiaa.org/content.cfm?pageid=226; "SAE International Scholarships Program," SAE International, 2010, http://students.sae.org/awdscholar/scholarships; "SME Student Scholarships," *Society for Mining, Metallurgy & Exploration*, n.d., http://www.smenet.org/scholarships.
607. National Science Foundation, *Proposal and Award Policies and Procedures Guide* (Arlington, VA: National Science Foundation, 2008), www.nsf.gov/pubs/policydocs/pappguide/nsf09_1/nsf091.pdf.
608. "DHS HS-STEM Summer Internship Program," *Oak Ridge Associated Universities*, n.d., www.orau.gov/dhsinternships/.
609. Richard W. Judy and Carol D'Amico, *Workforce 2020: Work and Workers in the 21st Century* (Indianapolis, IN: Hudson Institute, 1997).
610. Harry J. Holzer and Robert I. Lerman, *America's Forgotten Middle-Skill Jobs: Education and Training Requirements in the Next Decade and Beyond* (Washington, DC: Urban Institute, 2007), http://www.urban.org/UploadedPDF/411633_forgottenjobs.pdf.
611. Bronwyn Mauldin, *New Mexico's Forgotten Middle-Skill Jobs: Meeting the Demands of a 21st-Century Economy* (Washington, DC: National Skills Coalition, 2010), http://www.nationalskillscoalition.org/assets/reports-/skills2compete_forgottenjobs_nm_2010-04.pdf.
612. "The Honors College-Meet the Heltzers," *Appalachian State University*, 2008, http://www.honors.appstate.edu/about/meettheheltzers.php; Douglas Martin, "Harry Heltzer, 94, Inventor of Reflective Signs, Dies," *New York Times*, September 28, 2005, http://www.nytimes.com/2005/09/28/business/28heltzer.html.
613. U.S. Congress Joint Economic Committee, *Understanding the Economy: Unemployment among Young Workers*, 2010, http://jec.senate.gov/public/?a=Files.Serve&File_id=adaef80b-d1f3-479c-97e7-727f4c0d9ce6; Kathryn Anne Edwards and Alexander Hertel-Fernandez, *The Kids Aren't Alright: A Labor Market Analysis of Young Workers* (Washington, DC: Economic Policy Institute, 2010), http://epi.3cdn.net/1a64c4b1b06d2da39e_ulm6b5g3l.pdf; David Schepp, "Tough Times for Teens: Youth Employment Plunges in Recession," *DailyFinance*, May 27, 2010, http://www.dailyfinance.com/story/careers/recession-youth-employment-plunges/19492422/; Jamilah King, "Youth Jobs Hit Hard by Recession," *New America Media*, February 11, 2010, http://news.newamericamedia.org/news/view_article.html?article_id=12406207e3a3291f93ce306f2aca0650; David G. Blanchflower and Richard B. Freeman, *Youth Employment and Joblessness in Advanced Countries* (Chicago: University of Chicago Press, 2000).
614. For more information, see www.nrmp.org.
615. National Center for Education Statistics, *Digest of Education Statistics: 2009*.
616. David M. Hart, Zoltan J. Acs, and Spencer L. Tracy Jr., *High-Technology Immigrant Entrepreneurship in the U.S.*
617. Sunil Mithas and Henry C. Lucas, "Are Foreign IT Workers Cheaper? U.S. Visa Policies and Compensation of Information Technology Professionals."
618. Ibid.
619. Ibid.
620. William R. Kerr and William F. Lincoln, "The Supply Side of Innovation: H-1B Visa Reforms and U.S. Ethnic Invention."
621. Ibid.
622. Sunil Mithas and Henry C. Lucas, "Are Foreign IT Workers Cheaper? U.S. Visa Policies and Compensation of Information Technology Professionals."
623. Laura Litvan, "Senate Dems to give Federal Commission Say over Legal Immigration Workers," *Washington Post*, May 24, 2010, http://www.washingtonpost.com/wp-dyn/content/article/2010/05/23/AR2010052304034.html.
624. Mark C. Regets, *What Do People Do After Earning a Science and Engineering Bachelor's Degree?* (Arlington, VA: National Science Foundation, 2006), www.nsf.gov/statistics/infbrief/nsf06324/nsf06324.pdf.
625. Albert Michaels, "In the Footsteps of Archimedes: Mathematicians Working in Industry," *Science Careers*, December 16, 2005, http://sciencecareers.sciencemag.org/career_magazine/previous_issues/articles/2005_12_16/noDOI.702668492924438022.
626. "Manufacturing Institute: Skills Certification System," *Manufacturing Institute*, 2010, http://institute.nam.org/page/edu_workforce_skills_cert.
627. A more complete description of one skills-based approach is provided below by Jo Kahn, Career Systems Coordinator Oklahoma Department of Career and Technology Education.
628. Ibid.
629. "WorkKeys | Occupational Profiles," ACT, 2010, http://www.act.org/workkeys/analysis/occup.html.
630. Ibid.
631. Ibid.
632. "CCNA—Career Certifications & Paths," *Cisco Systems*, n.d., http://www.cisco.com/web/learning/le3/le2/le0/le9/learning_certification_type_home.html; "Oracle University Select Country," *Oracle*, n.d., http://www.oracle.com/us/education/selectcountry-new-079003.html; *National Council of Examiners for Engineering and Surveying*, n.d., http://www.ncees.org/; and "GRE," Educational Testing Service, 2010, http://www.ets.org/gre/.
633. A description of the Dutch Program, the Kenniswerkersregeling, can be found at http://www.senternovem.nl/kenniswerkers/ and http://archief.brainport.nl/Brainport_C01/Default.asp?CustID=354&ComID=32&ModID=2445&ItemID=0&SessionID=-1&bottest=
634. Peter Cappelli and Philip Miscimarra, "Workplace Challenges: Managing Layoffs, and Motivating Those Left Behind," interview by Knowledge@Wharton, Audio, November 24, 2009, http://knowledge.wharton.upenn.edu/article.cfm?articleid=2389.
635. The President's Council on Science and Technology recently recommended federal support to enable the creation of 200 new STEM high schools. President's Council of Advisors on Science and Technology, *Prepare and Inspire: K–12 Education in Science, Technology, Engineering, and Math (STEM) for America's Future (prepublication version)*.
636. Sponsors of the National STEM Video Game Challenge are AMD Foundation, Entertainment Software Association and Microsoft. Founding outreach partners include the American Association of School Librarians, American Library Association, Boys & Girls Clubs of America, BrainPOP, and The International Game Developers Association. See "Advancing Children's Learning in a Digital Age," *Joan Ganz Cooney Center*, 2010, http://www.cooneycenterprizes.org/.

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