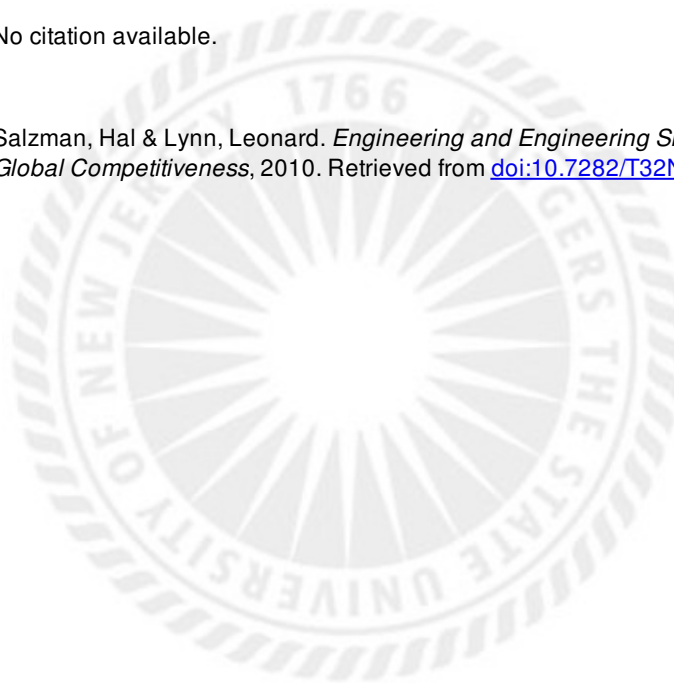


Engineering and Engineering Skills: What's Really Needed for Global Competitiveness

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Engineering and Engineering Skills:
What's *really* needed for global competitiveness

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Session on
*“What Do We Mean by Skills?
Implications for Education and Training Policy”*

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In the midst of a protracted economic crisis, coupled with persistent and outsized trade deficits, there has been a growing sense of insecurity about the ability of the United States to compete in the global economy. The answer, according to many policy analysts, is supporting and reinvigorating the U.S. strength in “breakthrough” innovation. Economic recovery, it is argued, will come from the types of innovation that delivered the Internet, the microchip, flat screen TVs, the iPod/Phone/Tablet, and more. To enhance its breakthrough innovation capability, many a policy report and social commentator argue, the United States needs to improve the level of math and science skills of its population. With such improvements in math and science performance, the argument goes, the United States can increase both the quality and quantity of its engineers and thereby restore its international competitiveness. The 2010 update of the National Academy of Sciences’ *Rising Above the Gathering Storm* report (National Academies of Science, 2007, 2010),¹ for example, identifies several largely “supply side” human resource deficits as the root of deteriorating U.S. innovation and economic performance. The report points to deficits in U.S. K-12 math and science education, the number of U.S. engineering students and graduates, and the number of U.S. engineers in the labor market. These deficits are also the presumed cause of the large numbers of foreign students (those on student visas) in U.S. science and engineering (S&E) programs, and the demand for guest worker visas (H-1B) to fill technology jobs. It is asserted that it is a lack of qualified S&E workers that drives the quest for students and workers from abroad.

This paper focuses on these “supply side” factors that allegedly threaten U.S. economic competitiveness. We examine the number of engineering students and graduates at various levels, and how well this supply of human resources matches what employers are seeking. We do find that there is some degree of mismatch, largely because of structural changes both in firms and in engineering work. This occurs at both the micro level (how engineering is practiced and the nature of technology development) and at the macro level (how firms are organizing their technology work globally and the labor force factors that affect the supply of engineers graduating from our universities). However, we find no evidence that deficits in the basic science and math education and the technical knowledge of U.S. students is leading to a shortage of highly qualified U.S. engineering students.

Improving the match between what employers need and what our current engineering graduates have to offer, we find, will require that students be provided better non-technical skills and capabilities. These non-technical skills are needed to enhance their effectiveness at working across organizational, technological and disciplinary, as well as cultural and national borders. The mismatch with employer needs stems from the increased importance of these new skills. The evidence suggests that the overall levels of math, science, and technical proficiency as well as the number of high-performing students in the United States are not a constraint on U.S. “competitiveness” (though improvements would, of course, be socially desirable). Consequently, we argue, an increased emphasis on narrow math and science education, as advocated in some policy prescriptions, may not be helpful, and could actually be counterproductive to improving the technological capabilities of the United States and its global “competitiveness.”

The Math and Science “Crisis”

In nearly every assessment of the U.S. economy and its educational system, two major issues of concern are the presumed poor levels of math and science performance by U.S. students in

¹ We address other aspects of the report in earlier papers (e.g., see Lowell and Salzman, 2007; Lynn and Salzman, 2010).

general and the actual number of high-performing math and science students the United States is educating². Shortcomings along these dimensions, it is claimed, are undercutting the United States' ability to create the human resources needed to ensure technological competitiveness. Elsewhere, we have addressed in detail the absolute and relative performance of U.S. students in math and science (Lowell and Salzman, 2007; Salzman and Lowell, 2008; Lynn and Salzman, 2010) and so we will only summarize those findings here. Overall, U.S. students³ have been steadily increasing their math and science performance. They have been taking more math and science classes on average, and more students now take advanced math and science classes (e.g., AP classes) so both the breadth and depth of math and science education are steadily improving. As can be seen from the figures in the Appendix, there is no evidence of a decline in student achievement, though of course these statistics do not reflect problems in particular populations, or in the nature of the distribution.⁴ Large problems do exist, for example in low-income and urban areas, and these are important problems to address for U.S. economic performance, but they are not directly related to the adequacy of the supply of engineers and scientists in the United States (Nor does it hold that average student test scores are integrally linked to economic outcomes and a nation's position in the global economy.⁵).

² Some of the widely-noted reports include those by National Association of Manufacturers (2005), *The Looming Workforce Crisis*; National Center on Education and the Economy (2007). *Tough Choices or Tough Times: The Report of the New Commission on the Skills of the American Workforce*; National Commission on Excellence in Education (1983), *A Nation at Risk: The Imperative for Educational Reform, A Report to the Nation and the Secretary of Education United States Department of Education*, and Council on Competitiveness (2004), *Innovate America*.

The education rankings cited in these and other reports include those from the PISA international education tests (Organisation for Economic Co-operation and Development (2003, 2004, 2006). The critiques of these rankings in particular and of the overall problems in interpretation of international and domestic testing results are discussed in Lowell and Salzman (2007), Salzman and Lowell, 2008, Rothstein (1998), Rothstein, et al., (2006), Ravitch (2010).

³ We use "U.S. students" to denote all students who are citizens whether native or naturalized, and those who are permanent residents (i.e., those with green cards).

⁴ The slight declines in average performance by 12th graders on standardized tests paradoxically may well indicate an improvement. Analysts of these tests, including the Educational Testing Service, find the declines are due to a broader range of the population taking the test rather than a year-to-year decline in comparable populations (e.g., see Lowell and Salzman, 2007 for further discussion).

⁵ In a bit of loose reasoning, some of those pointing with alarm to comparative test scores cite the fact that students in a number of mostly small countries, such as Finland and Estonia, score better than their American counterparts. No one identifies these countries as economic or military threats to the United States. Strangely enough, the threats that critics worry most about come from China and India. Yet neither China nor India participates in the international tests; if they did on a nationwide basis, they would no doubt score quite low, given the problems these countries have had in extending their education systems to poorer and more remote areas. Indeed, in India more than a third of the population is illiterate (United Nations Development Program, 2009). The countries leading in literacy rates are all former Soviet Bloc countries, with Cuba and Georgia leading the list. The United States is 19th, with China and India placing 80th and 147th, respectively. Similarly, the United Nations' education index (using a composite of several education achievement factors) provides a similar ranking, with the United States ranking below Iceland, Cuba, Slovenia, and Barbados (United Nations Development Program, 2009). Clearly, the educational rankings list appears to be quite unrelated to rankings of economic performance. Since no one would suggest that these nations are economic or political models for the United States, it is not clear what significance high test scores have for outcomes other than the test performance itself.

There are broader problems with arguments based on relative U.S. student performance on tests such as the Programme for International Student Assessment (PISA) or Trends in International Mathematics and Science Study (TIMSS), the two major international education tests (Organisation for Economic Co-operation and Development (2003, 2004, 2006). The tests do *not* actually show the United States to be seriously lagging the world. On average, the United States scores solidly in a second-place group of countries on some subjects and in the first tier on others. It is one of only a few nations that shows consistent improvements or stability in performance from year to year and over all grades and subjects. In fact, a number of states within the United States that are similar in size to the "leading" countries, such as Singapore and Finland, do as well as or even better than these countries (Lowell and Salzman, 2007; Salzman, 2007; Salzman and Lowell, 2008).

The second aspect of engineering supply is whether the United States produces a sufficient number of high performing students as compared to other nations. If we accept the notion that it is the absolute size of the top-performing student pool that is important for the size and output of the engineering workforce, then it is important to recognize that the United States currently produces a group of highest-performing students in science as well as in reading that is many times greater than that of any other nation, and in math that is second only to Japan⁶ (Salzman and Lowell, 2008; see Figures 1A, 1B, and 1C).

Overall, in terms of level, quantity, and consistency across all subjects, the United States has a stock of top-performing domestic students that is larger than that of any other country. The United States achieves this performance level despite having a population that is economically and socially much more diverse than that of any other industrialized country.⁷ The proportion of top-performing math and science students has not wavered over the past three decades and, with the growing U.S. population, this has resulted in ever-greater numbers of top-performing math and science graduates. Indeed, the number of these graduates far exceeds the employment opportunities in the science and engineering fields each year (Lowell and Salzman, 2007; Salzman, 2007; Salzman and Lowell, 2008). In fact, due to the 2007-2009 decline in the economy, the United States' *oversupply* of engineering graduates has grown — only 42 percent of 2009 engineering graduates found jobs, a decline from prior years in which 70 percent of engineering graduates found engineering jobs (Walker, 2010).

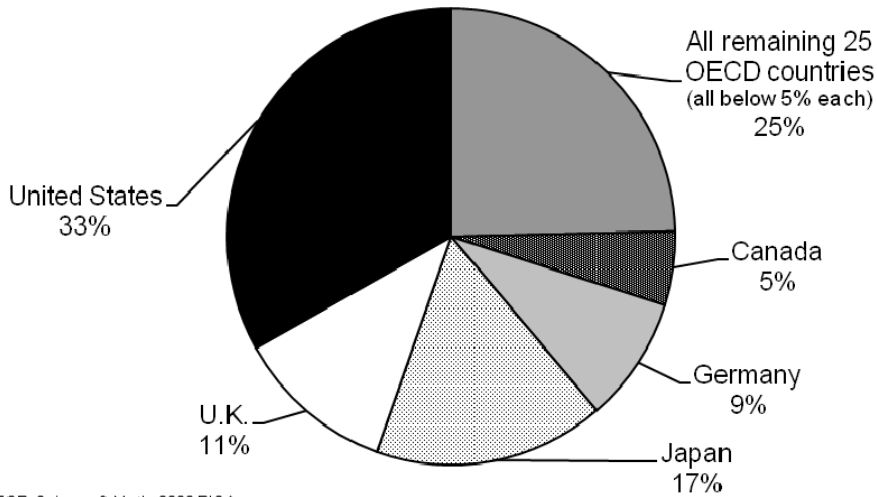
Given such low levels of apparent demand for engineers, increasing the supply of engineers can be viewed as neither necessary nor desirable. And, calls to increase the math and science skills toward that end, which might easily entail shifting resources from other areas of education, as was advocated in the National Academy of Sciences' 2010 report *Rising Above the Gathering Storm*, seem similarly unwarranted. Certainly K-12 education is important, and we do not wish to encourage complacency with the U.S. system, particularly since the United States also has a large group of very poorly performing students. Yet it is misguided to base the argument for improving the math and science skills of students on exaggerated views of how this might speed up economic growth or how it might help the United States close imagined gaps with other countries.⁸ Of course, the nation should make education a top priority for a range of reasons, including not only economic prosperity but also civic engagement, promoting more equality of economic opportunity, and the overall development of our population. However, when it comes to the role of education in supporting economic competitiveness, the use of narrow criteria of uncertain validity, such as K-12 math and science test scores, may lead us to overlook the demands for a broad range of other skills or the need to improve basic skills at the bottom of the distribution.

⁶ However, since the math test questions use metric measurements and the Japanese testing appear to use a different sampling method than the U.S. testing, the Japanese advantage may reflect these artifacts rather than true differences. See Lowell and Salzman, 2007 for more detail on this.

⁷ The United States stands alone among Organisation for Economic Co-operation and Development OCED countries in the degree of non-school achievement factors long shown to negatively affect academic performance (e.g., non-native language spoken at home, poverty, single-head household).

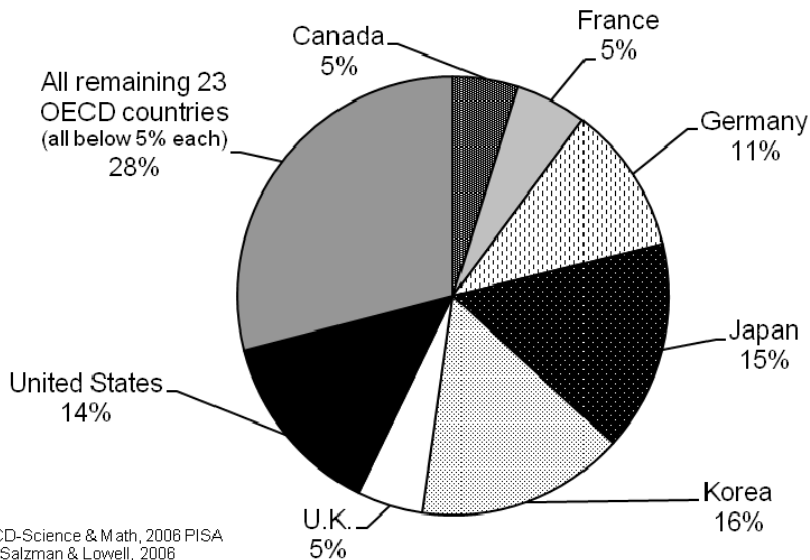
⁸ Further, it seems questionable to define the goals of the U.S. education system in terms of a “race” with other countries to achieve higher K-12 math and science test scores. Some countries may have education systems that are part of, and reflect political systems inimical to, American values, such as those operating under autocratic or authoritarian rule. Many countries have not been able to translate high test scores into any tangible innovative or economic performance (e.g., Latvia or Moldavia today, or the other Communist bloc countries during the cold war. Top-scoring Finland, with over a quarter of its youth unemployed, also ranks high in overall unemployment. [Statistics Finland, 2010]). More importantly, as we will discuss, it is the overall “competitiveness” strategy that the United States develops as a roadmap for economic and social well-being in the global economy that should guide the workforce development component of education and training programs.

Figure 1A.
Percentage of all OECD high-performing students in science



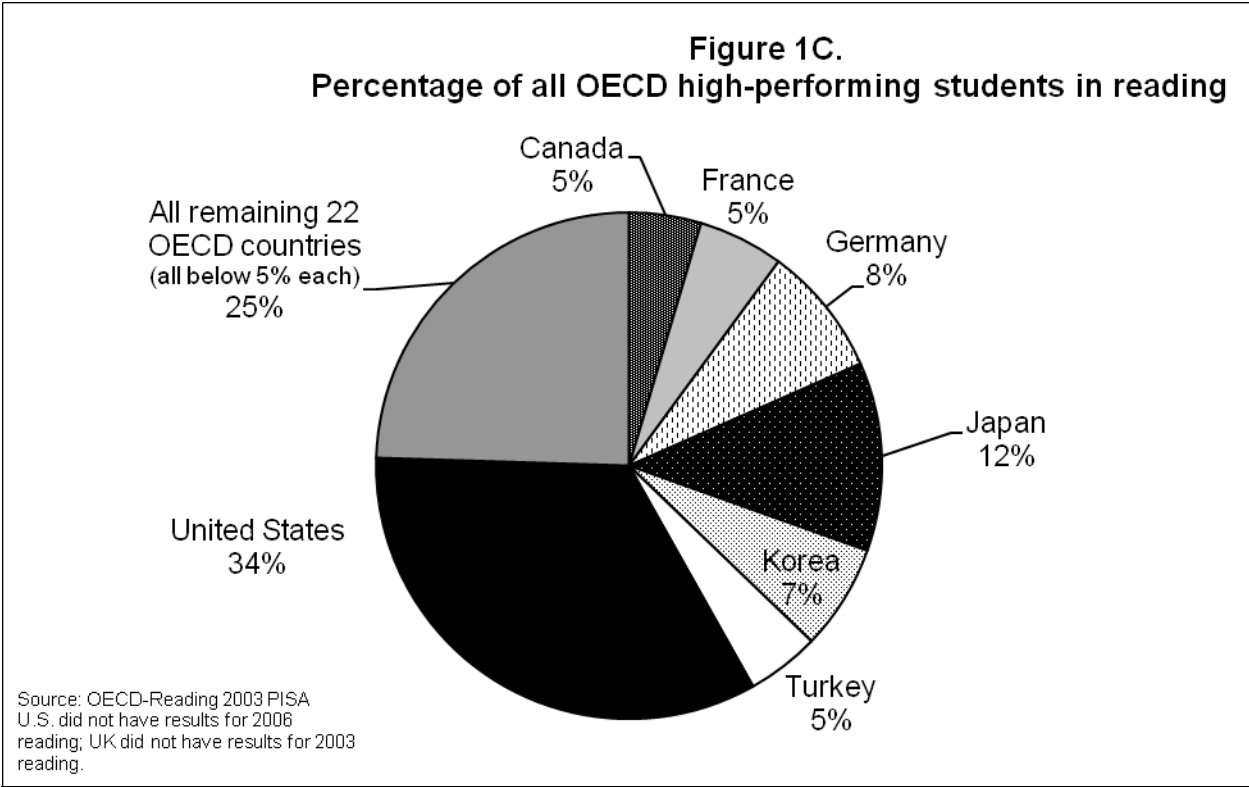
Source: OECD-Science & Math, 2006 PISA
 Tabulations: Salzman & Lowell, 2006

Figure 1B.
Percentage of all OECD high-performing students in math



Source: OECD-Science & Math, 2006 PISA
 Tabulations: Salzman & Lowell, 2006

In the next section, we examine the supply of and demand for engineers, and the role of engineering in a nation's economy. Here again we challenge the evidence underlying some commonplace assumptions.



[These figures are reproduced from: Salzman and Lowell, 2008; “Making the Grade” *Nature* 453, 28-30]

Does the United States produce enough engineers?

The question of the adequacy of the U.S. supply of engineers has two dimensions. Are our universities graduating a sufficient number of engineers to meet domestic labor market demand? And, is the number of graduates they are producing sufficient, relative to other countries, to maintain or increase our comparative advantage in technological development/innovation? A related question concerns the ability of our universities to attract and graduate sufficient numbers of *domestic* students to fill their classrooms (e.g., Wadhwa, 2010). To be sure, it may be desirable to encourage talented foreign students to come to U.S. universities to enrich the classroom experience of U.S. students by increasing global diversity. Some may see the attraction of foreign students as a strategy of having talent from around the globe located in the United States rather than in countries that are seen as “competitors” (perhaps as a contemporary replay of the post-World War II scramble between the United States and the U.S.S.R. to get the best German rocket scientists). More positively it can be a way of educating students who will return home and enrich their country’s stock of human resources. The question here, however, is whether U.S. engineering programs and businesses have become overly dependant on foreign students and that the reason for this dependence is a shortage of domestic students capable and willing to fill out the engineer ranks of our workforce. To address that question, we examine the numbers of engineers being graduated in the United States and China. This will allow us to examine the drivers of labor force demand and the implications for innovation and technology development. We then address the question of whether the U.S. economy has a sufficient number of engineers to support its economy. We also address the related question of whether U.S. colleges are sufficiently responsive to labor market demands for engineers.

The Engineer Race

Concerns that the United States may be losing a test-score race with other countries are often linked to concerns that the United States is losing a race with other countries in the number of engineers it is educating. Numerous reports point with alarm to statistics that show rapid increases in the number of engineers being trained in India, China, and other countries. The implication is that if China and India have more engineers than the United States, this somehow puts the United States at risk. The proposed solution to this “problem” is to train more Americans to be engineers (partly by increasing Americans’ interest in science and engineering and partly by improving science and math education in grades K-12). Although increasing the numbers of educated workers is intrinsically a laudable goal, does the engineering workforce size in other countries provide useful guidance for U.S. workforce development policy? To answer that question, we need to examine what engineers do and what drives the market for engineers.

In our analysis of engineering occupations and the nature of demand for engineers (Lynn and Salzman, 2010), we find that engineers make up just over 1 percent of the civilian workforce. Nearly half of all engineers are civil, mechanical, and industrial engineers, with 56 percent of all engineers working in either manufacturing or construction. Not quite 5 percent (4.8 percent, or just over 75,000) are in “scientific research and development services,” and it seems likely that only a few percent more are involved in key innovation activities (Bureau of Labor Statistics, 2010). Thus, most engineers are not creating new technology or developing “breakthrough innovations.” Instead, they are designing bridges, roads, power plants, factories, and buildings, or running day-to-day manufacturing operations.

China is rapidly developing, and its engineers are doing what a rapidly developing country needs its engineers to do. Chinese engineers are building new manufacturing facilities and power plants, expanding cities, and constructing new bridges, railways, and highways. In comparison to the more than 30,000 miles of new interstate highway China built in the past decade, for example, the United States added only 608 additional miles (Lynn and Salzman, 2010). While China is building thousands of miles of additional rail and waterway transit, the United States has actually seen a decline in its total mileage of both. As a proxy of construction and manufacturing activities, it is illustrative to compare the national consumption of cement and steel, two key inputs for construction and manufacturing. As Lynn and Salzman (2010) show, in Table 1 and Figure 2, China is ravenously consuming these inputs while U.S. consumption has remained flat.

| | United States¹ | China² |
|-----------------------|----------------------------------|--------------------------|
| Length, Miles | | |
| Interstate/Expressway | 608 | 30,519 |
| Navigable Channels | (680) | 8,510 |
| Rail | (4,030) | 7,436 |

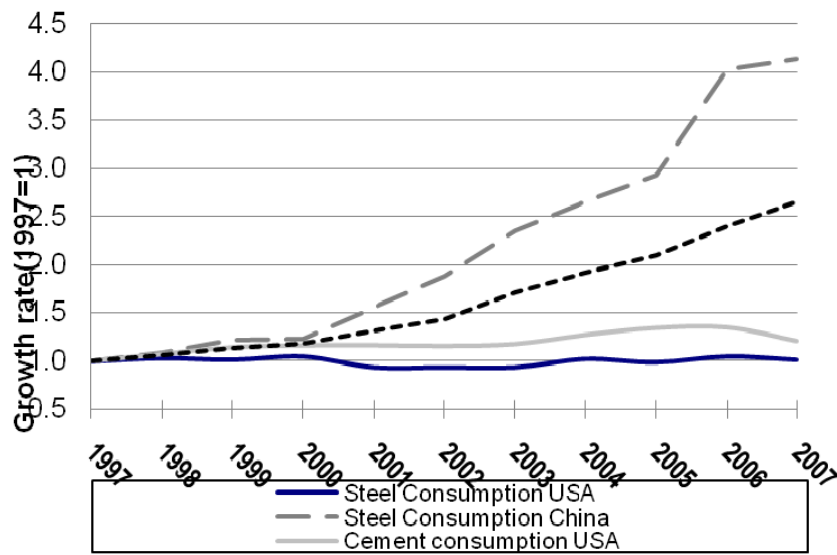
(From: Lynn and Salzman, 2010)

Sources:

1. National Transport Statistics, 2009. Bureau of Transport Statistics, U.S. Department of Transportation.

2. China Statistical Yearbook, 2008. National Bureau of Statistics of China.

Figure 2. Steel and cement consumption* in the United States and China, 1997-2007



Sources:

-U.S. Steel:USGS Mineral commodity summaries, Iron and steel.

-China Steel:(1998-2005) OECD, Recent steel market developments, 28 June 2004.

-China Steel(1997): OECD, The steel market in 1997 and the outlook for 1998 and 1999.

*USA cement consumption = production(excluding clinker)+import for consumption(excluding clinker)- exports

*China cement consumption = production - export

Consequently, we should expect parallel trends in the production and employment of human resources used for that building and manufacturing. In China, it is the rapid development of the economy from a relatively low level that is generating the demand for engineers. Thus, it hardly seems remarkable that in 2008 China felt a need to graduate approximately 660,000 engineers from a population of 1.3 billion people to add to a total workforce of over 780 million. The vast increase in the number of engineers in China is focused on meeting rather basic infrastructure and natural resource needs. It is not indicative of an engineering arms race that threatens the relative U.S. ability to innovate or to compete.

Beyond the numbers, however, is the question of skills. There is no doubt that China can recruit huge numbers of bright students to its universities and then outpace the United States in the number of engineers it graduates. But, what of the skills these engineers graduate with, and what of their employability? The one serious study of engineering supply in China and India (Gereffi, Wadhwa, Rissing, and Ong, 2008) looked beyond the aggregate numbers and examined the types and quality of engineering graduates in these countries. They find that a small number of graduates from the elite universities are in high demand, but the vast majority do not have the skills or qualifications that global firms need. They make a further distinction in “type” of engineer, between “transactional” and “dynamic” engineers. The former are those who have technical expertise but not the “experience or expertise to apply this knowledge to larger domains (p. 21).” It is dynamic engineers that have those latter skills and there are very few of those graduating from Chinese and Indian universities. A McKinsey study finds that only 10 percent of China’s engineering graduates are considered employable in global firms, compared to over 80 percent of U.S. engineering graduates (as cited in Farrell and Grant, 2005). Adjusting for quality, then, China is graduating fewer internationally qualified engineers than the United States (66,000 qualified Chinese engineering graduates compared to more than 80,000 American bachelor’s and master’s

engineering graduates [National Science Board, 2010a]). This is what should be expected at this stage in China's history. Without the depth of faculty who have engineering experience or involvement with firms doing leading-edge engineering, it would be difficult to quickly develop the ability to provide large numbers of engineering students with the skill needed to reach global standards.

You can never be too thin or too rich...or have too many engineers?

The supply side question is addressed by the "more-is-better" advocates in two ways. First, they imply that breakthrough innovation can be driven from the supply side, (i.e. that the more engineers that are produced, the higher the levels of innovation that can be expected. How these engineers will produce innovation without employment in their occupation is a question left unanswered).⁹ The point should be not how many engineers are trained; it should be how many of those trained are actively working as engineers. And, as was just previously discussed, it must also be noted that most engineering graduates, perhaps well over 90 percent of them, have jobs that have little to do with innovation.

Second, the advocates for increasing the supply of engineering graduates assert that an engineering education is desirable in itself because it provides transferrable skills to other fields that are uniquely valuable for the modern economy, especially the management of technology and technology development. Putting aside speculation that many people trained in engineering are likely frustrated by an inability to find jobs in their preferred field, it may be useful to consider the evidence for the fungibility of engineering skills. While it is likely that engineering provides a fine technical education and that it does provide many transferrable skills, there is little evidence of any unique advantage provided to a country that artificially produces more engineers than it has jobs in engineering.¹⁰ In fact, some evidence suggests that an engineering degree is becoming less important in other fields, including the management of technology occupations. Lowell et al. (forthcoming) examine the composition of STEM (science, technology, engineering and mathematics) managers between 1993 and 2003. In both years, the largest group of STEM managers were those who hold a non-STEM degree (including MBAs), but there was a shift from 1993 to 2003 in the next largest group from engineering graduates (declining from 14.7 percent of STEM management job holders to only 8.1 percent) to social science graduates (rising to 11.8 percent of STEM managers in 2003). If we look at the composition of STEM managers who hold a STEM degree (i.e., excluding the non-STEM degree holders, and using the National Science Foundation's definition of STEM which includes social scientists), as shown in Figures 3 and 4, we find a similar shift:

In 1993, 41.1 percent of the STEM-educated STEM managers have Engineering degrees (compared to 21.2 having Social Science degrees, and 20.1 percent having Physical and Biological Sciences degrees). In 2003, 35.9 percent of the STEM-educated STEM managers have Social Science degrees, and only 24.5

⁹ Typically, about a third of each year's engineering graduates do not find jobs in an engineering field, and following the financial meltdown, more than half of new U.S. graduates did not find engineering jobs in 2009 (Walker, 2010).

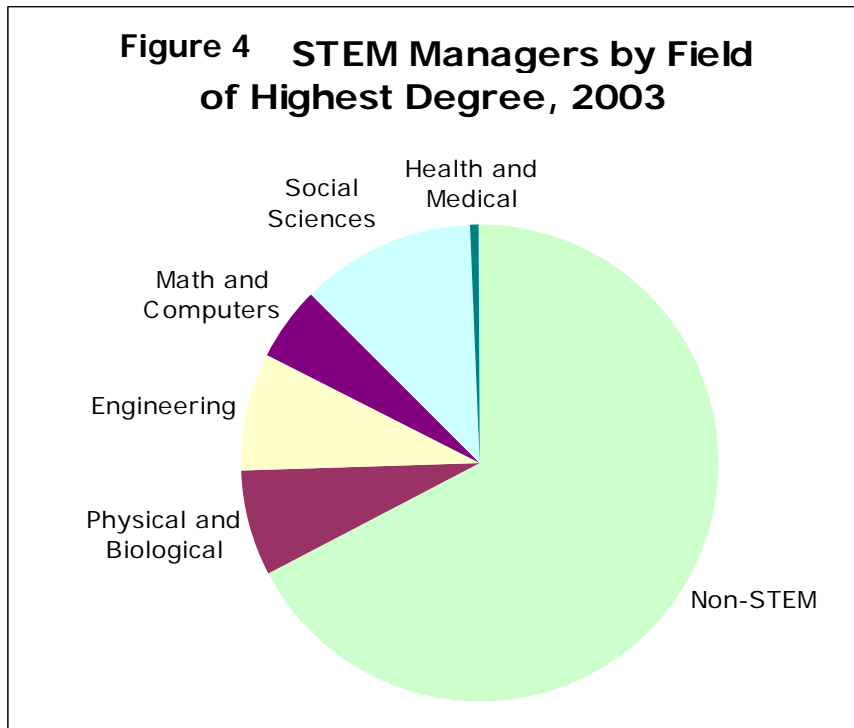
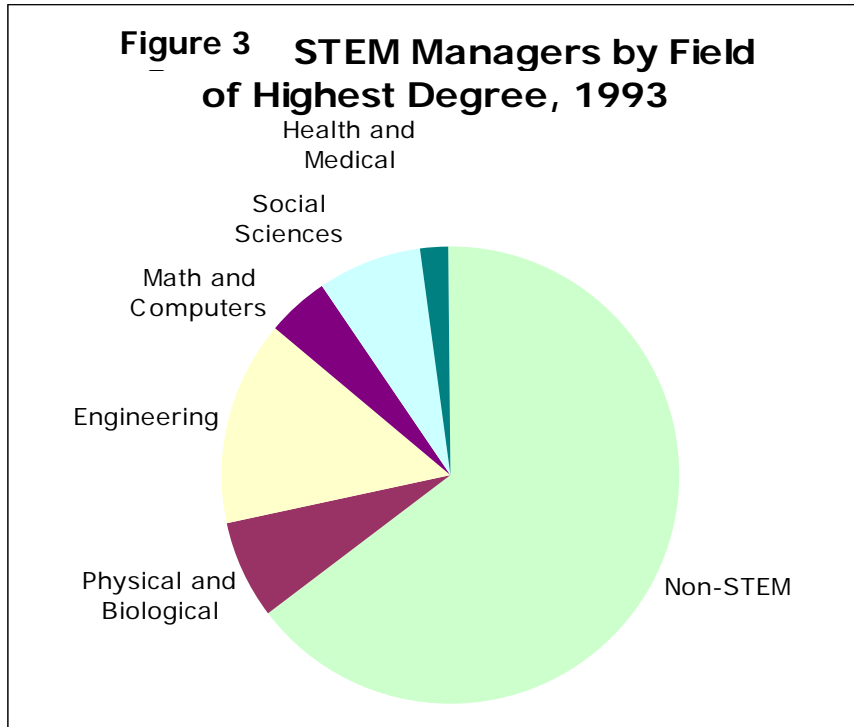
¹⁰ In our interviews with engineering managers and discussions with our MBA students with engineering undergraduate degrees, we have been told repeatedly how difficult it is for people with engineering degrees to make the transition to management. An engineering education tends to reinforce the notion that there are "right" answers to every question and these answers can be systematically determined by following one rule or another. There is little room for emotional intelligence and not much patience with ill-defined problems. It may be that our current system for the education of engineers is dysfunctional when it comes to training people who will not actually become bench engineers.

percent have Engineering degrees, followed once again by 22.1 percent having Physical and Biological sciences degrees (Lowell, et al., forthcoming).

At the same time, however, more engineers are moving away from engineering and into management. The proportion of engineers with a Bachelors degree going into management doubled, from 11 percent in 1993 to 22 percent in 2003.¹¹ In other words, over the 1990s, non-STEM majors and Social Science majors seem to have pushed out engineers and other hard STEM degree holders from some STEM Management positions they formerly dominated (Lowell, et al., forthcoming). Overall, a greater proportion of graduates in all fields except health/medical are in management over this period. While these data don't provide information about why this has occurred, it is consistent with the findings of our field work, discussed below, on the restructuring, globalization, and outsourcing and offshoring of engineering work (and probably some job title inflation as well).

In summary, the data do not support the notion that an engineering degree offers a compelling advantage in STEM management. Indeed, over time, engineering degrees seem to have become less valued for STEM management relative to other degrees, particularly compared to social science degrees. This shift has implications for the types of skills needed in engineering education and in the education of engineers and STEM managers. It is consistent with employer concerns that too few engineers have the "soft skills" of communications, the ability to work across organizations, the possession of a broader perspective of the non-technical aspects of engineering work and production, and other aspects of management. We address the change in content and skill requirements identified by employers below, but first we turn to the final piece of the supply question — how responsive is the supply of engineers in the United States to the demand for engineers?

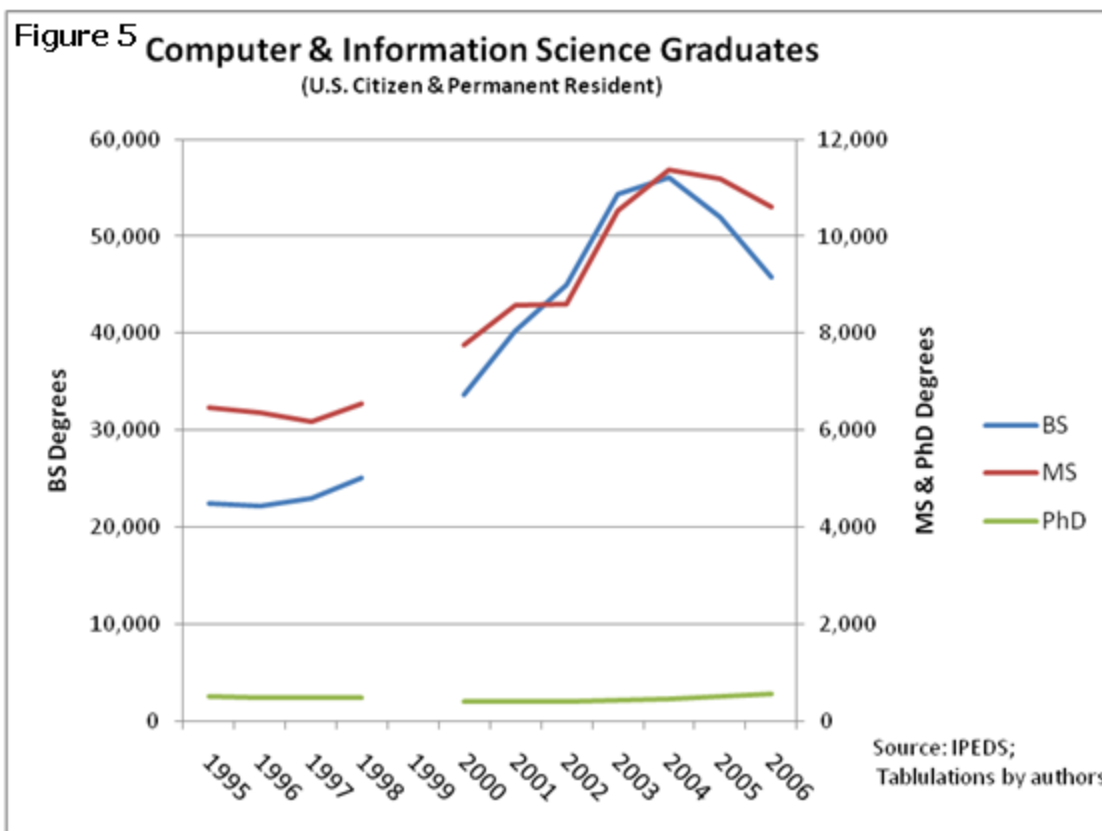
¹¹ For engineers with a Master's degree, however, the increase was minimal, from 14.1 percent in 1993 to 15.5 percent in 2003.



[From: Lowell, Salzman, Bernstein, and Busquets, forthcoming]

Are U.S. colleges and universities responsive to market demands for engineers?

An underlying assumption of the supply side advocates is that increasing the extent and breadth of K-12 math and science education would eventually result in an increase in engineering graduates. The logic is, apparently, that there is an insufficient number of U.S. high school graduates with adequate math and science skills to satisfy the “demand” of U.S. universities for qualified engineering students. Our analyses, however, suggest that whatever weaknesses there are in U.S. K-12 math and science education, these weaknesses do not hinder the development of an ample supply of top-performing students available to pursue engineering degrees. Another possible problem might be that our colleges and universities are too inflexible to respond to changing market demands for graduates coming from the various different engineering disciplines, educating too many in a declining field and not enough in a growing field. If so, this could partially account for the low employment of engineering graduates. To provide some evidence related to this question we examine the trends in two engineering fields where there were significant rapid changes in demand.



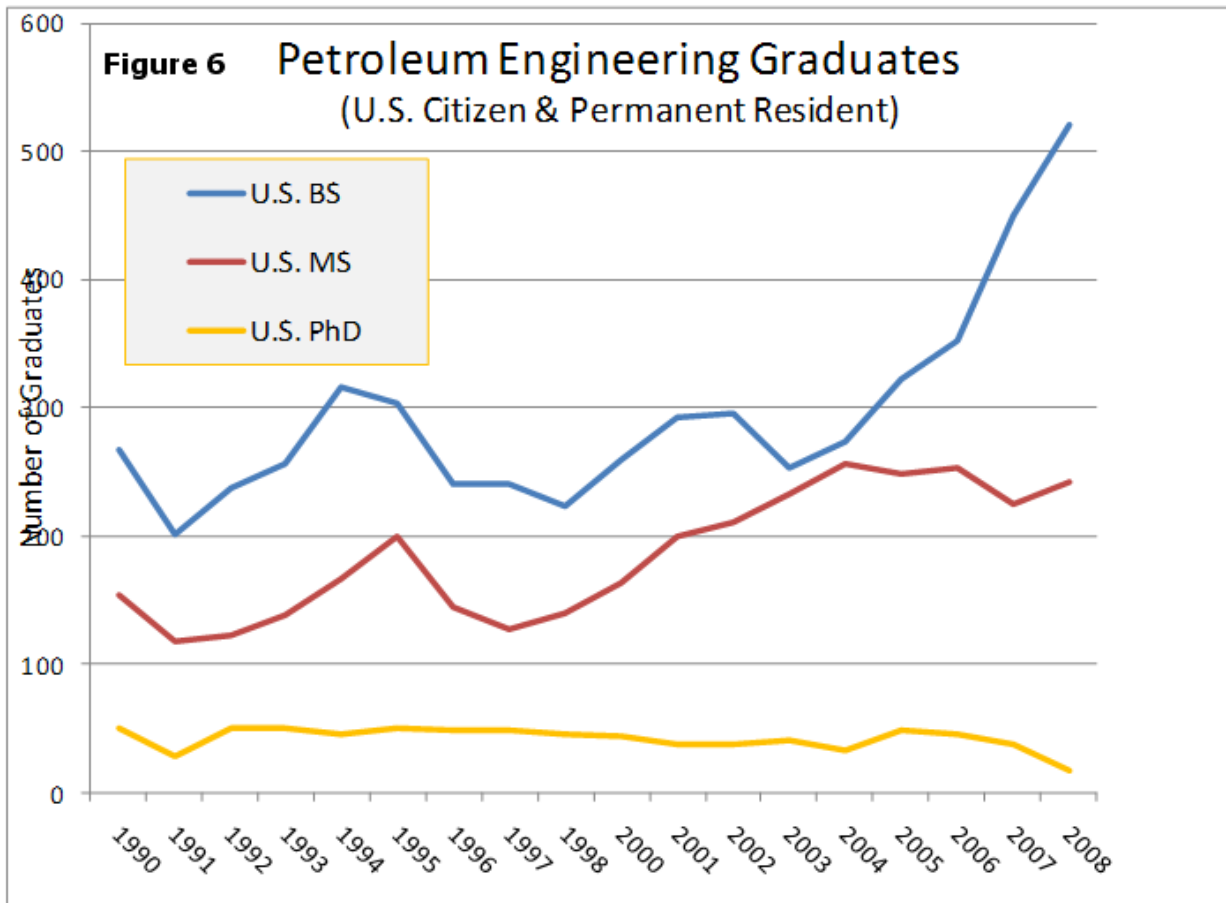
As we entered the 21st century, the demand for IT workers was rapidly increasing. This sudden increase was in part the result of a technology bubble, largely in the dot-com sector, combined with a temporary confluence of industry-specific factors related to the Y2K conversion, implementation of new software systems, and the growth of several new software languages and technologies (e.g., see Salzman, 2000, and Salzman and Biswas, 2000). As Figure 5 shows, in response to the spike in demand, the number of graduates rapidly increased in the first years of the century. Conversely, in response to the technology bust and the remediation of Y2K problems and system conversions, the number of graduates rapidly declined.

A second case is that of petroleum engineers. In the 1970s, the building of the Trans-Alaskan Pipeline and increased oil exploration in other regions led to rapidly increasing demand for petroleum engineers. By 2002, the Occupational Outlook forecast an employment decline “because most of the petroleum-producing areas in the United States already have been explored” (BLS, 2004) and this continued to be the forecast through the 2008 edition of Occupational Outlook. In the most recent edition, 2010-11, however, the BLS forecast changed to an employment *increase* of 18 percent over the coming decade because “petroleum engineers increasingly will be needed to develop new resources, as well as new methods of extracting more from existing sources.”¹² The shift to greater exploration followed the 2008 oil price spike, which also increased the returns to investments in types of oil extraction that were previously cost-prohibitive (e.g., tar sands), thus increasing the demand for petroleum engineers, especially those with new skill sets

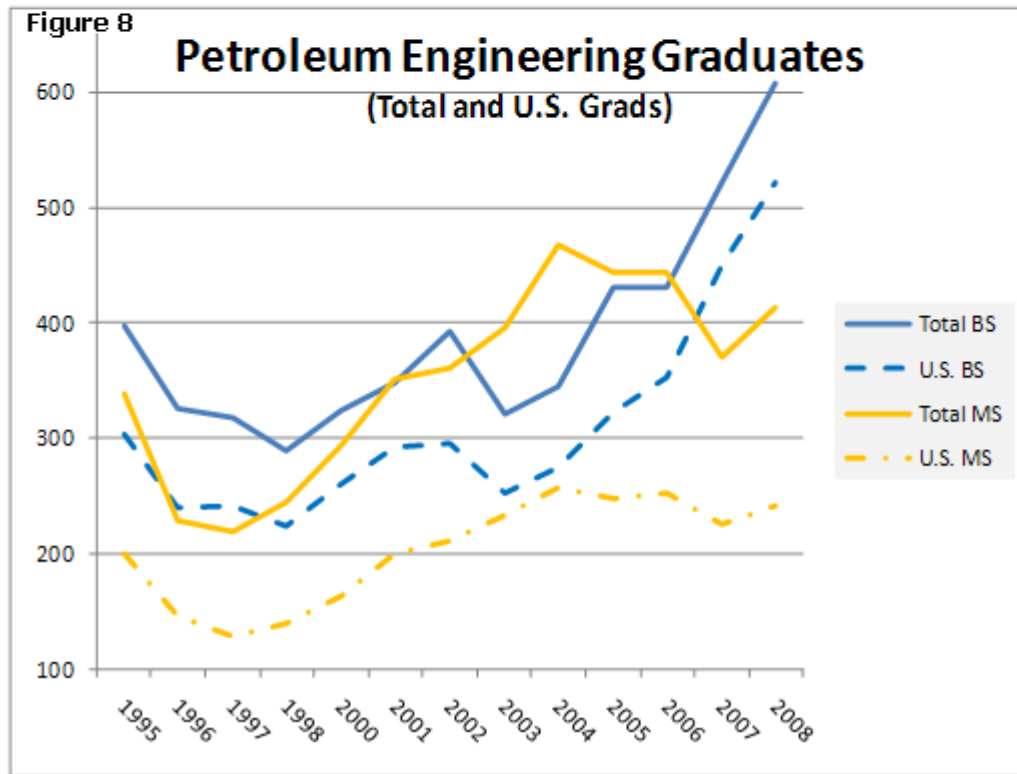
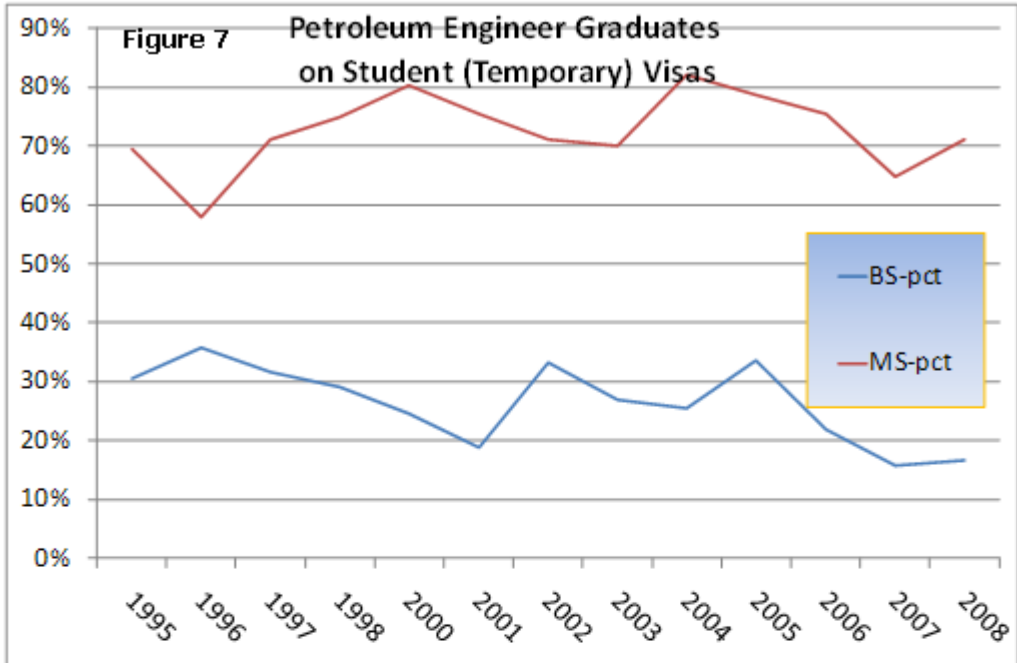
In terms of employment, however, the job openings began to exceed the number of graduates around 2002, even though there was no overall workforce growth. This was because of retirements. In some interviews with managers in oil companies, we found high levels of concern about the large cohort of retiring engineers just as they were launching large development and maintenance projects. This underlying demand was then exacerbated by the oil price spike, which intensified exploration efforts, in part because higher oil prices would make previously unprofitable exploration profitable. The earlier shortage had already led to increases in starting salaries, but with the oil price spike, petroleum engineering starting salaries rose further, becoming the highest of all fields of engineering for new bachelor’s degree graduates (National Association of Colleges and Employers, 2010). Starting salaries jumped from an already high \$43,674 in 1997 to \$50,400 in 1999. Starting salaries rose further to \$55,987 (Bureau of Labor Statistics, 2004) in 2003, \$61,516 in 2005 (Bureau of Labor Statistics, 2006), and \$86,220 in 2010 (National Association of Colleges and Employers, 2010). In all these years, petroleum engineering salaries were higher than other engineering salaries but, until recently, the petroleum engineering starting salary premium was small. For example, the 1997 \$43,674 starting salary for petroleum engineers was only marginally greater than that for the second highest paid engineering field, chemical engineers, who received an average starting salary of \$42,817. In 2010, however, the starting salary of \$86,220 for petroleum engineers was much higher than that of the second highest field, still chemical engineering, which was only \$65,142 (National Association of Colleges and Employers, 2010).

As shown in Figure 6, the number of petroleum engineering graduates increased dramatically as wages and demand increased. Reports from some petroleum engineering programs show an even greater increase in demand in the past two years (TTU, 2010). Most industry demand is at the Bachelor’s level, which is evident in the sharp divergence of Bachelor’s and Master’s degrees. We infer that the decline in Master’s degrees was a result of Bachelor’s degree graduates entering directly into industry rather than pursuing a Master’s degree (an issue we are currently researching; this would be consistent with the trend we found for Computer and Information Science degrees during the dot-com boom).

¹² (<http://www.bls.gov/oco/ocos027.htm>)



Interestingly, it is not just the overall supply of petroleum engineering graduates from colleges that appears to be responsive to demand and wages, but it is the domestic supply (U.S. citizens and permanent residents) in particular that supplies the increased pool of graduates. As wages increase and job demand in the United States increases, there is a shift in the relative share of domestic and foreign students; the percentage of foreign petroleum engineering graduates here on student visas, the highest of any of the engineering fields at the bachelor's level, declines as the domestic supply increases (Figures 7 and 8). At the Bachelor's level, the number and percent of total graduates who are on student visas dropped to the lowest proportion of total graduates in the past 15 years. The share of graduates on student visas dropped from slightly more than half of the proportion from 13 years ago (17 percent in 1995 vs. 31 percent in 2008), even though the actual number of student visa graduates increased or held steady. The increased demand was largely satisfied by American students.



[Source: IPEDS; Tabulations: Kuehn and Salzman]

In summary, this evidence suggests that concerns about the supply of engineers, and/or concerns about the ability of U.S. schools to provide an adequate supply of students with the qualifications to become engineers in response to demonstrated demand, are ill-founded. There is a steady, if slow, increase in the math and science capabilities of the best American students and in the supply of students. Moreover, colleges appear to have been quite able to increase their production of engineering graduates (and domestic students) when there is sufficient market demand and incentives, at least in the cases of computer/information sciences and petroleum engineers.

Perhaps, before we worry unduly about how many engineers we are graduating, we need to worry about how many our economy can productively employ. We need to worry about why many engineering graduates are unable to find jobs in engineering, and what signals that sends to current students deciding what careers to pursue. Perhaps our economy cannot productively use many more engineers than we are now educating. Or perhaps we have a shortage of engineering graduates with the skills that make them valuable to firms and effective as entrepreneurs. Before making any dramatic changes in our supply of engineers, we need a better understanding of the demand side of the equation. Otherwise, we risk unintended outcomes that can distort labor markets and the attractiveness of these fields for years to come. The boom–bust cycle of engineering employment following Sputnik made engineering an unattractive career opportunity for many years following the dramatic employment declines in the late 1960s and through the 1970s (Kaiser, in preparation; Freeman, 1976). More recently, the expansion of science doctorates has led to a decline in the appeal of those degrees to prospective students (Teitelbaum, 2008). Conversely, the tight control over the number of medical degrees offered in the United States has kept that field highly desirable to qualified young people, but at the cost to society of physician shortages. Thus, while restricting the number of degrees may come at an immediate social cost of shortages, artificially inflating the numbers, and thus distorting the market, ultimately devalues the longer-term attractiveness of the profession and exacts a high social cost as well.

The lessons learned from past decades of demand and supply in the science and engineering labor market are that disequilibria have significant consequences and that market-driven adjustments seem to occur reasonably well, albeit with a short lag given the years of preparation needed before workforce entry (Freeman, 1976; Teitelbaum, 2008).

What skills do engineers need?

The evidence presented to this point addresses the oft-asserted claims that K-12 schools are not educating enough students with adequate math and science skills, either in absolute numbers or relative to other countries that are considered to be economic competitors, and to the claims that our colleges cannot increase the supply of engineering graduates to meet industry demand. A related claim, that there is an overall need for more engineers because other countries such as China are increasing their production of engineers, is also inconsistent with what is known about the demand for engineers. That said, there is still the question about what skills engineers do need to be productive in today's economy. It is on that point that our research and that of others (e.g., Sheppard, et al., 2008) does indicate an area that needs to be addressed.

The findings reported here draw on four studies by the authors with colleagues on changes in manufacturing engineering in the United States, Germany, and Japan, on the IT industry and skills demands, on globally distributed engineering by U.S. and European multinationals, and on the

science and engineering workforce education and demand.¹³ Interviews were conducted at over 100 company sites with more than 300 individuals. Although many of our findings on skill and workforce development are specific to a particular engineering field, the company being studied, and/or the country site, there are also several findings that are common and consistent across all the companies, jobs, countries, and fields. These findings reflect the changing structure of industries, organizations, and technologies and are part of a broader organizational restructuring of manufacturing firms over the past two decades (e.g., see Moss, Salzman, and Tilly, 2001; Hira and Hira, 2005).

Overall, we find some degree of mismatch between the skills current engineers have and the skills that employers say they are seeking. In interviews with engineers and managers in a wide range of firms, we find consistent reports of skill deficits. These skill deficits are broadly identified as communications skills and the related ability to work across a variety of “borders” — organizational, technological, disciplinary, as well as cultural and national. Interestingly, we have not been told by a single manager that recently hired engineers in the U.S. were lacking appropriate technical skills, nor have the managers we interviewed had difficulty finding engineers with good technical skills.

Boundary-spanning skills

Our research suggests that the most essential upgrading of engineering education needed to ensure U.S. technological competitiveness is less a deepening of specific technical skills than it is imparting new boundary-spanning skills.

Skills spanning engineering discipline boundaries. One of the projects we are drawing from in this paper began as a study of manufacturing engineers. Sponsors of the pilot phase of this project believed that researchers had neglected this important facet of engineering and wanted to bring new attention to manufacturing. We quickly found, however, that research focused specifically on ‘manufacturing engineers’ would provide only a limited understanding of how firms are increasingly managing their engineering activities in today’s environment. Notwithstanding the importance of manufacturing *engineering*, the role of manufacturing *engineers* can only be understood in a broader context. We found that the companies in our study had apparently responded to the criticisms of the past decades about the siloing of engineering functions, particularly the widely noted complaints about design work being done without regard to manufacturability.¹⁴ We also were struck by the overwhelming importance of pressures to escape from the “not invented here (NIH) syndrome,” in which technologists focused too much on

¹³ The research was supported through grants from the National Science Foundation (Human and Social Dynamics Program, #SES-0527584; Social Dimensions of Engineering, Science and Technology #0431755), the Alfred P. Sloan Foundation (with Lindsay Lowell), and by the Ewing Marion Kauffman Foundation to study technology entrepreneurship and globalization, and the National Academy of Sciences for the study on the IT industry. These projects were conducted with colleagues including Lindsay Lowell, Pamela Meil, and Radha Biswas. The international studies were conducted in collaboration with colleagues in Germany (Pamela Meil, ISF—Munich), Mexico (Carlos Acosta, UDLA-Puebla), Tojo Thatchenkerry (George Mason University, with expertise in India), in India (Balaji Parthasarathy, IIIT-Bangalore; P. Vigneswara Ilavarasan, IIT-Delhi), China (Wang Zhong-Ming, Zhejiang University), Korea (Geon-Cheol Shin, Kyunghee University). These colleagues helped us with contacts and interviews and greatly stimulated our thinking. The authors, however, are solely responsible for any conclusions reported in this paper. Detailed findings from these studies are reported in Lynn and Salzman, 2002, 2004, 2006, 2007a, 2007b, 2008, 2009, 2010; Lynn, Salzman, and Meil, forthcoming; Salzman and Meil, 2010; Lowell and Salzman, 2007, 2009; Salzman and Lowell, 2008..

¹⁴ For a summary of many of these complaints in both U.S. and Japanese multinationals, see Kono and Lynn, 2007.

developing their own solutions to technical problems, as firms were more willing to outsource and to use more off-the-shelf technology (Katz and Allen, 1982). These changes resulted in a blurring of the boundaries between engineering functions. Thus, although a design engineer may have the primary responsibility for product design, the actual design activity occurs in collaboration with other engineering functions or even as a team process with manufacturing engineers.¹⁵ The result is major changes in the role of manufacturing engineers and the development of new roles for different functional engineering groups.

These findings are consistent with a growing body of research on how the practice of manufacturing engineering is changing in the United States, and perhaps in the rest of the world as well. Many observers see an increased overlapping in the duties of product development and manufacturing engineers, combined with various recent techniques intended to improve manufacturing such as “Just-in-Time (JIT) and “Total Quality Management” (TQM) systems, and time-based competition to make manufacturing better able to cope with disturbances and variability (Lynn, 1982, 2009; Hobday, 2000). The result has been a more integrated systems approach that requires broadly trained technicians and engineers. The design, operation, and management of more integrated systems present greater requirements for social skills, effective team participation, initiative, and entrepreneurial capability (for discussion of characteristics of engineering profession from an earlier era, see Meiksins and Smith, 1996).

Consistent with this point, there has been a blurring of the distinction between product development and manufacturing engineering with the introduction of concurrent engineering and shorter product development cycles. Manufacturing engineers and product development engineers frequently work together from early on in the product development process in order to make production easier. In the latter stages of product development, manufacturing engineers and production engineers work together to transfer technology to the manufacturing process and to run trials.

It is interesting to note that some universities in the United States are offering degrees specifically in “manufacturing engineering,” which is somewhat distinct from the traditional engineering fields. Manufacturing engineering is characterized in this context as “hands on” applied engineering. As a discipline, it is based on less advanced math than is true of the traditional engineering disciplines (e.g., requiring college algebra and trigonometry and only a little calculus). In part, this development is in response to industry surveys, which show a need for engineers with greater social breadth and communications skills. In an earlier response to this perceived need, ARBET (the Accreditation Board for Engineering and Technology) changed requirements to require that a minimum of 20 percent of coursework be done in these areas (Worthley, 1995).

As noted above, in some firms the distinction between manufacturing engineers and, for example, product development engineers is not clear cut. At an electronics firm we visited, the vice president for engineering described the functions of manufacturing engineers and product development engineers, but also mentioned another type of engineer, the “manufacturing bridge engineer.” These engineers put new products into production, bridging the design and production functions. The bridge engineers stay in the manufacturing function until the completion of five production cycles. In one automobile parts supplier, all products are designed by a team — a design engineer has primary responsibility for actual design work, but there is also an engineer who is the project manager, with responsibility for interacting with the customer on design specifications (with much of the design specification done by the Original Equipment Manufacturer [OEM]), and the

¹⁵ This development was first widely noted in studies of the Toyota manufacturing system, see, for example Fujimoto, 1999; Liker, 2004. Unfortunately for Japan, Japanese firms proved to be unusually poor at certain other forms of boundary spanning, see Porter, Yakeuchi, and Sakakibara, 2000.

manufacturing engineer who is involved from the beginning in design reviews. Similar shared responsibility was found at a high-technology electronics firm as well. In one firm characterized by rapid product turnover, research, development, and engineering functions are all under the same vice president.

In the product design area, managers complained about engineers who had an overly technical focus and didn't understand the broader perspective of the technology or products in the market. Several criticisms were made of designs that were "good engineering," but poor from the business standpoint.¹⁶ Consistent with observed trends toward boundary spanning in engineering, design engineers are expected to participate collegially with other engineers. In the past they might not have listened to the concerns of manufacturing engineers, pushing through their decisions without building consensus — approaches that are not acceptable in the current environment.

Communications skills to span organizational, cultural, and other boundaries. The boundaries that engineers increasingly need to span are not just those between engineering disciplines. One U.S. manager said that the day of the brilliant engineer who would lock himself in his lab and slide his findings out under the door was over. Another mentioned firing an engineer who was outstanding on the technical side, but disruptive to the organization — the engineer was more concerned with proving he was smarter than everyone else than in accomplishing project missions. Engineers have to be more adept than ever before at "communicating." This has become a "core" engineering skill. Managers typically said that technical skills were fairly easy to find and *not* a good criterion for distinguishing between candidates. Rather, it was the ability to communicate their ideas, to work with others on a team and with non-engineers, and other related social skills that were more reliable indicators of success. These skills reflect the changes in the nature of engineering work, ranging from greater teamwork, working across disciplines, with customers, and interacting with customers and suppliers in developing and acquiring technology (Lynn and Salzman, 2002).

Of course, as will be noted below, a few engineers are recognized as being high performers based on purely technical skills. A far larger number of the higher performers, however, were seen as having good (but not necessarily exceptional) problem-solving and analytic skills, but the major factor distinguishing them was that they accomplished their job through good structure, organization, and, most importantly, knowing how to get help and other resources to accomplish the job. One U.S. engineering manager in our study said: "Good engineers get things done. One aspect of this is the completion of work...a good engineer uses trial and error to push things further. Getting the job done also means a thoroughness in problem-solving in the case of manufacturing." This manager judges engineers based on their success at completing assignments. Another respondent wondered if there was much difference between what made a good engineer and what made a good manager. At a Japanese automobile company, respondents indicated that successful engineers are those who can push their project through by mobilizing people and resources. Managerial, negotiation, and communication skills are seen as essential. One young U.S. engineer identified by senior managers as a "high performer" explained in an interview that while he wasn't the most technically excellent engineer in his group, he knew how to get help when he needed it and was well organized so his projects were completed on time. Successful engineers actively take the initiative in developing their own skills.

While several managers indicated that they had a few engineers with such exceptional technical skills, that a lack of interpersonal skills could be overlooked, these cases were unusual.

¹⁶ In our comparative study of criteria of engineering excellence in the United States, Germany, and Japan, U.S. managers seemed to view this as particularly problematic with German engineers (See Lynn and Salzman, 2002).

One manager commented that such technically brilliant people without the social and managerial “soft” skills belong in universities rather than in business. This manager offered the example of a recent engineer he hired who was “brilliant, an excellent mathematician,” but was unable to explain the value of his ideas to his team — and this engineer didn’t see the need to improve his communications skills, so he was let go. The vice president for engineering of a tier-one automotive components supplier gave two examples of instances where engineers were excellent in the accomplishment of technical goals, but were still downgraded in annual performance reviews. In one, an engineer was openly disdainful of the ability of other engineers at the company or its customers. His/her manager might be called and asked never to send that engineer to work with them again. In another, an engineer was asked to work with more junior engineers to solve a problem. Instead, he would concentrate his efforts on finding a “brilliant” solution to the problem without involving others. The problem might be solved, but the opportunity to train others would be lost. We were surprised that even with probing, engineering managers did not indicate that technical skills are difficult to obtain in the U.S. labor market. The managers believed that most college engineering programs are rigorous enough, and/or that self-selection weeds out those lacking the requisite technical abilities.

A final example further illustrates the new skills needed by engineers. Engineering managers at one of the firms in our study mentioned recently hiring an engineer who was not outstanding by their technical criteria, but was enthusiastic about the company’s international activities. The managers were somewhat surprised by this young engineer’s global interests, especially that he would welcome a foreign assignment. Most of their technical staff had no interest in working overseas in exotic emerging economies. This new breed of engineer proved to be a wonderful asset for the company because he was not just willing, but actually eager to accept assignments in emerging economies.

Behind the Changing Structure of Engineering Work.

A number of changes in the global environment underlie the changes we observed in the needs employers have for their engineers. These include a wide range of organizational, technological, and business strategy changes that over the past 10 to 20 years have led to new skill requirements for engineers and other technical workers.

The de-integration of technology activity is a factor that increasingly requires engineers to work across organizational boundaries with suppliers. Products that are based on tightly integrated technology of different types, such as electronic and mechanical, or different materials, increasingly require engineers to work across disciplines, often with engineers in different fields. Business strategies that place more emphasis on market-driven technology development also require engineers to understand the business drivers as well as the technology drivers of product or service development. And, perhaps most notably, is the changing global structure of firms, leading to what we term “globally distributed engineering” in which firms locate significant engineering activities across different, geographically dispersed sites.

The overall changes in globalization patterns are historically disjunctive, leading to the emergence of what we’ve referred to as the “Third Generation Globalization” of knowledge work (Lynn and Salzman, 2004, 2006).¹⁷ The Internet, new collaborative technologies, and reduced travel

¹⁷ The “first generation” was characteristic of the first two or three decades after World War II. Multinationals (most of which were American) maintained technology development functions near corporate headquarters in the home country; products at later stages in the product life cycle were sold and sometimes manufactured in emerging economies. During the “second generation,” some knowledge work was transferred to other developed economies, but the knowledge work

and communications costs made it possible for globally distributed teams to work together on technology projects. The reduction of barriers to international activity in the wake of the establishment of the World Trade Organization and a new enthusiasm for foreign direct investment by China, India and other emerging economies gave new incentives for firms to offshore, as did the rapidly growing wealth of large new markets. These changes reached the threshold of maturity and acceptance in firms in the early 2000s (e.g., see Thursby and Thursby, 2006). By the middle of the decade, firms had created globally distributed teams that regularly interacted in projects (Flecker and Meil, 2011). A group of managers at a U.S. multinational in the electronics industry told us during interviews in 2005 that 10 years before, they and their offshore teams had barely known each other. By 2005, they were in telephone contact several times a week. A vice president at a chemical firm told us in 2004 how engineers were now being sent offshore on six-month projects while continuing to participate in their U.S.-based product development teams. Earlier, they had been sent overseas on three-year assignments and had only sporadic relationships with the firm's engineers based in the United States. And more recently, short-term, offshore assignments or extended trips have become more common.

Other changes also make this third generation of the globalization of knowledge work different from its predecessors. Centers of technological excellence began to develop in some of the emerging economies. Some multinational enterprises (MNEs) found it useful to seek new sources of Science and Technology (S&T) human resources and knowledge near these centers. In our interviews at U.S. MNEs, we were repeatedly told about highly valued Chinese or Indian engineering or R&D managers who were now reaching later stages in their careers in the United States and wanted to return home. These managers made a persuasive business case for the MNE to locate R&D or product development activities in their home countries. Moving these core activities to an emerging economy would have been unthinkable before the changes in technology, international trade environment, corporate structures and strategies, and emerging economic governmental policies that frame the third generation of knowledge work. Nor would these managers have had much interest in moving their family back to impoverished home countries before these countries had begun to provide safe and comfortable environments.

In parallel, as was noted above, U.S., EU and Japanese MNEs moved from a bias against NIH technology to trying to find ways to outsource technology development. The conventional wisdom was that outsourcing saved money, and financial analysts liked to hear corporate managers describe aggressive outsourcing targets (Lynn and Salzman, 2009). In some industries, new models of modular production led to an increased reliance on Original Equipment Manufacturer (OEM) and Original Design Manufacture (ODM) firms in emerging economies. Technologies increasingly crossed traditional boundaries of industrial expertise, and it seemed that no firm, no matter how large, could possibly master every relevant technology. In fact, it became a management truism that large firms are by nature resistant to innovation. Innovation, it was thought, increasingly came from startups and small firms. With the increased mobility of people and companies and radically improved means of storing and moving information, knowledge flows far more rapidly and supports collaborations that are both more tightly linked and more globally dispersed.

More recently, the global distribution of engineering work has added another layer of non-technical positions for the technically adept. The new global engineers and managers are different from engineers of the past. The new global engineers are very open to cosmopolitan experiences. While many of the non-technical skills valued by employers of engineers can be provided through

assigned to emerging economies was primarily intended to adapt products to local conditions, often by “dumbing down” technology to make products easier to manufacture or use under more primitive conditions. Some technology-related activities were grudgingly assigned to emerging economies as a price for market access.

broad-based, multi-disciplinary education, some appear to come from cross-national experiences. Increasingly the ability to span cultures and nations is a key attribute. We found a special, usually unacknowledged position of global liaison technical manager who served as a bridge across a firm's different geographies. In most cases although these people were educated in the United States, they were not born in the United States but had lived in more than one different country. Perhaps this can be taught, but it may also require educators to incorporate cross-national experiences as part of technical training.

The new globalization patterns require new engineering practices and, with that, new skills to enable engineers to successfully conduct engineering work. But these changes in skill requirements are less about engineering content than about the supporting skills that enable engineers to work in the new environment of globally distributed engineering. One set of skills includes the communications, interpersonal, organizational, and cultural skills that facilitate work and management across all the various boundaries mentioned above. These different boundary-spanning skills and abilities are increasingly important, especially in firms that are systems integrators, the firms at the higher value-added part of the development chain.

Implications for Education Policy

Solid math, science, and technology education obviously provides an essential foundation for the skills required by engineers. However, globally competitive engineering education must go far beyond training technically competent graduates. A broad education that incorporates a range of technical *and* social science *and* humanities knowledge is increasingly important for maintaining and developing a globally competitive workforce (e.g., see Hill, 2007). In this, the United States as a multi-cultural society with diverse international roots, could have an important advantage over most other countries. Good education programs targeted at improving U.S. competitiveness might incorporate greater efforts to inspire the curiosity of each student about her/his cultural heritage and also encourage more foreign language education. A focus on engineering without consideration of its cultural context is another shortcoming in a system that has long enjoyed dominance and position of setting global standards. An appreciation for other cultures is not just a human resources diversity initiative but a core engineering requirement to understand the global context of new technology needs and that of the growing markets for products and services.

The weaknesses in our engineering education system when it comes to meeting employer needs are not the science and technology aspects of the system. Indeed, it seems likely the global diffusion of science and technology (S&T) work away from the United States is primarily caused by other factors such as the "catching up" of China, India, and other countries where markets are growing faster than in the United States, the removal of barriers to the movement of technology (third-generation globalization), and the opportunity of global talent arbitrage (for lower S&T labor costs) than any deficit of technical skills in the United States (on trade policy and competitiveness, see also, Gomory and Baumol, 2000). In any case, a strategy for the U.S. of trying to compete with China and India on the basis of sheer numbers of technically competent scientists and engineers is untenable and is unlikely to provide the basis for achieving sustainable economic growth.

In the third-generation globalization era of technology development, engineers are more likely to work and live outside their home countries, and even at home are more likely to find themselves working in cross-national teams. In this world, might not training in foreign culture and languages be as important as further enhancing the already high skills in math and science of the U.S. engineering workforce? Might not design, humanities, and social sciences be important to understanding consumer needs and developing innovative consumer products, as has proven to be the case with various Apple products that are distinguished by far more than the purely technical aspects of their engineering. But providing the full portfolio of needed skills cannot be done by

simply taking a “finishing school” approach to engineering education. Rather, it must be incorporated into what is considered essential education, alongside and as important as math and science throughout the educational curriculum in universities and in K-12 schools.

While it may seem paradoxical to say so, in our view the best education policies to promote U.S. economic competitiveness are not those that are narrowly concerned with competition — producing more engineering students and more engineers than other countries or giving U.S. students the highest scores on narrowly defined achievement on standardized math and science tests. The best policies are those that educate large numbers of Americans to span boundaries of culture, country, specialization, and organization. The best policies are those that will facilitate an American ability to profit from productive cooperation with the rest of the world.¹⁸

APPENDIX

High School Course Taking and Performance

Appendix 1A Science, math, and language course taking

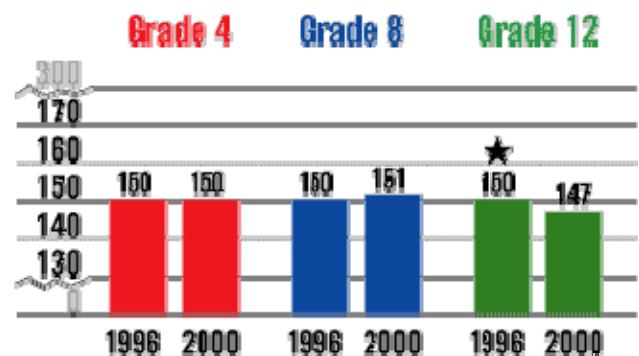
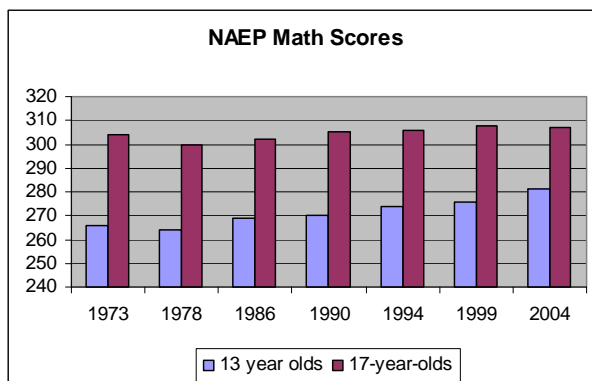
Appendix 1B Test scores (Source: National Center for Education Statistics; National Assessment of Educational Progress)

Appendix 1C SAT scores

Appendix 1D Math and science scores by percentile rank

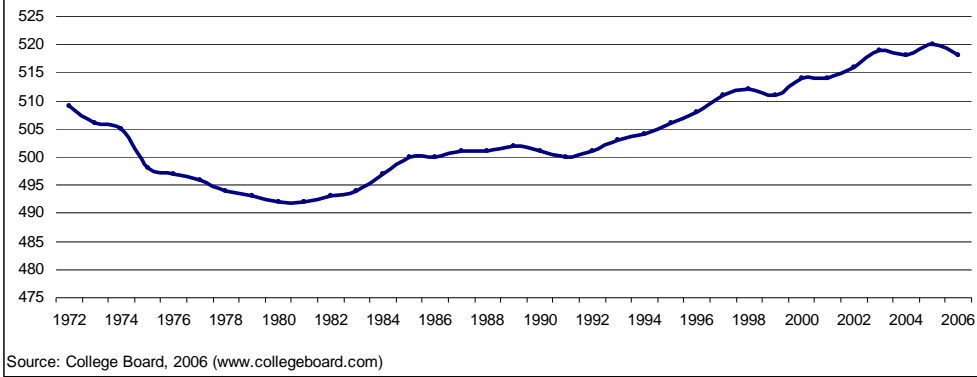
| Average number of Carnegie units earned by public high school graduates | | | | |
|---|-------|------|---------|------------------|
| | Total | Math | Science | Foreign language |
| 1990 grads | 23.5 | 3.2 | 2.8 | 1.5 |
| 2000 grads | 26.1 | 3.6 | 3.2 | 2.0 |

NAEP Science Test Scores 1996 and 2000

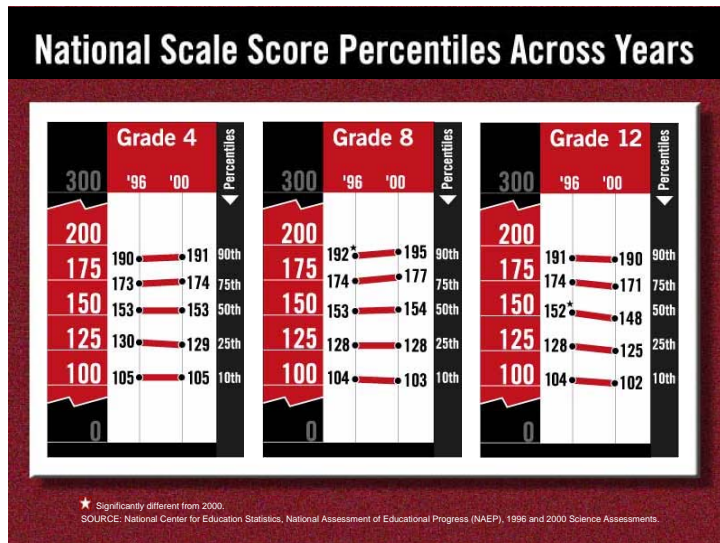


¹⁸ This thought is developed further in Lynn and Salzman, 2006.

Figure 2. College-Bound Seniors Total SAT Math Scores, 1972 to 2006



NAEP Science Test Scores, 1996-2000



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