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US Science and Technology Leadership, and Technology Grand Challenges

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Abstract

The US enjoys a science and technology (S&T) enterprise that is the envy of the world. Our universities, industries, laboratories, and government institutions have developed and used technology that has driven economic benefits and secured superpower defense status. The US remains the leader in S&T innovation, a position enjoyed since World War II. While the health of the US S&T enterprise remains strong, there are considerable stresses within each major component. Some believe that the US position as leader in S&T could falter, at least in some fields. We review the stresses in various components of the S&T enterprise and the evidence of trends in S&T quality. We conclude that the enterprise maintains a leadership position for now.

We believe that this leadership position, in order to be maintained, requires specific challenges, to aim at "goalposts." While most of the work in the S&T fields result in incremental improvements to products and capabilities, certain grand challenges are within our grasp if the science and technology community is provided with specific directions and priorities. Much as the 1961 call by then-President Kennedy, for a manned mission to the moon and safe return with a deadline of less than a decade, provided an impetus for advances and accomplishments that benefited the nation, national security, and society in general, so too it should be possible to develop certain specific applications in reasonable time-frames that achieve new specific goals. In a second part of this paper, we survey a range of application domains and potential grand challenges that could be accomplished with concerted efforts by the S&T community.

Keywords: science, technology, S&T policy, S&T leadership, futurism, technology transition, technology challenges

Part A: The US Science and Technology Landscape: Department of Defense Perspectives

Introduction

From Benjamin Franklin to today, the United States has had a history of developing and leveraging science and technology. American innovativeness was noted by de Tocqueville, and is a hallmark of the birth and maturation of the nation. World War II marked an acceleration in US investment in science and technology, not only because of the development of nuclear weapons, but also with the immigration of large numbers of accomplished European scientists, and a national sense of appreciation for the benefits of science and technology research.

Vannever Bush is credited with codifying these benefits in his essay "The Endless Frontier," (1) and designing the policies that have led to US superiority in most areas of

S&T. Today, scientists and technologists throughout the world have come to American universities and American S&T institutions because of this leadership position. The US has led the world in publications, quality of laboratories, university rankings, and innovations.

Technology leadership has benefited the United States generally. The US Department of Defense (DoD) has specifically benefited from this position. The US has been able to acquire advanced weapons and defense systems far earlier than adversaries, and has used technology to offset disadvantages that could have otherwise created vulnerabilities. Among the many important technology innovations that have benefitted the US military, well known examples are surveillance systems, space technology, microelectronics, networking and communications, precision weapons, and stealth technology. Many of the advances benefited society in general. DoD has funded much of the innovative science research that gave rise to these benefits.

Technology leadership also has led to the creation and growth of high technology businesses, which in turn provided societal benefits and economic strength. A succession of high technology companies can attribute their rise to US technological leadership—companies such as IBM, Boeing, Apple, and Google.

Global interest in science and technology

In recent years, many nations around the world have sought to increase their investments in research, with the intention of developing an ability to innovate "indigenously." As a result, there has been concern as to whether the US lead in science and technology might be in jeopardy (2). Most conclude correctly that the US vanguard in S&T remains substantial, but that the lead cannot be taken for granted.

Total US investment in research and development (R&D) has fallen from about 38% of the world's total in 1999 to 31% in 2009 (the last year for which data is available). This decline in the percentage of total R&D expenditures (in purchasing power parity) has occurred despite US increases in R&D spending that have outpaced growth in GDP, rising to about 2.8% of GDP in recent years (3).[i]

One argument says that more R&D, and more technology, is a good thing for mankind, no matter who is in the lead. After all, most research is reported in open literature, and is available for transition by anyone with the capital to do so. Historically, however, technology leadership has been an advantage and "fast-followers" have not experienced the same benefits. With globalization of research, some feel this differential will erode, and that science is increasingly confronting "global challenges" vice national or parochial interests (4). Research as a global enterprise, which is fueled by ubiquitous and cheap communications, is part of the "global systemic shift" (5) that provides a framework for understanding societal and cultural shifts due to technological and demographic changes. With the benefits of research investments becoming more diffuse, it becomes more difficult to achieve unique returns. In order to avoid the atrophying of research intensity, investors must see the possibility of returns, and thus ongoing R&D efforts require new models of technology development.

Science "corridors" and "science parks" have become important models for many nations. Based on the Silicon Valley model, they are now being pursued throughout the world, often located in university communities.[ii] While the mere existence of science parks does not guarantee a local entrepreneurial environment and economic activity (6), they are evidence of a world-wide interest in science and technology incubation, and provide the possibility of information exchange that can foster local business development. The Science Park and Innovation Center Association's directory lists 157 "Science and Technology Parks" and "Technology Business Incubators" located throughout China (7). In the US, a major effort in New York City to recreate Silicon Valley is taking place under the name of "Silicon Alley" (8, 9). While technology parks are a manifestation of interest in S&T investment, they are only one component of an extensive science and technology enterprise within any given nation. In the US, that enterprise is distributed throughout universities, industries, government, and laboratories.

The National Science Board (NSB) sponsors an annual study by the National Science Foundation on science and engineering indicators, providing detailed data on trends both nationally and internationally of the science and technology enterprise. Summarizing the concern from a great deal of data, the NSB committee chairperson states the case while speaking about the loss of high-tech manufacturing jobs over the past decade:

> *"The latest data clearly show the economic consequences of the eroding competitive advantage the United States has historically enjoyed in science and*

> *technology," said Dr. José-Marie Griffiths, chairman of the NSB committee that oversees production of the report. "Other nations clearly recognize the economic and social benefits of investing in R&D and education, and they are challenging the United States leadership position. We're seeing the result in the very real, and substantial, loss of good jobs."*
>
> *"The volume gives a clear picture of the United States' position in globalization," said Griffiths. "Over the last decade, the world has changed dramatically. It's now a world with very different actors who have made advancement in science and technology a top priority. And many of the troubling trends we're seeing are now very well established." (10)*

While those troubling trends involve manufacturing jobs, they also portend a potential challenge to US science and technology leadership. Of course, the notion of science and technology leadership raises issues of "globally relevant" policies, ethics, and standards in the conduct and sharing of research. For example, in biomedical research, when should advances be shared and drugs made affordable in the global commons, and how should global researchers leverage the talents and knowledge of others (11)? Clearly, there is a balance required between maintaining incentives for global leadership in science and technology, and rapid dissemination, sharing, and collaboration in the research enterprise. Without models that maintain incentives, the health of the enterprise could easily falter.

While the health of the S&T enterprise in the US remains good, there are important challenges and ways in which the US could do better, and there is a need to constantly strengthen and reinvigorate the enterprise.

The structure of the US S&T enterprise

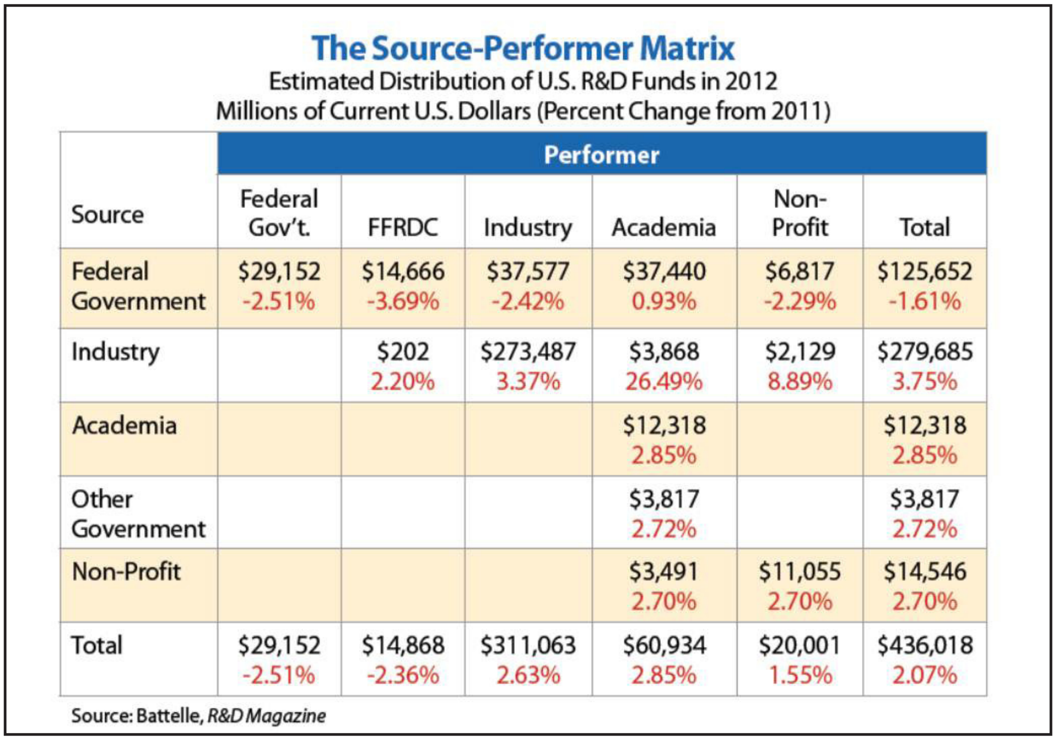
The US science and technology enterprise is distributed throughout society, but principally lies within the following structures:

- Academia;
- US industries and multinationals with a US presence;
- The US government, including military service labs and research labs;
- Federally-funded research and development centers, and university-affiliated research centers; and
- Non-profits and foundations, retirees in societies, and others.

Estimates from the OECD indicate the US has in excess of 1.4 million researchers as of 2007, distributed among these entities, engaged in research and development. In that year, Europe also had close to 1.4 million researchers, out of an estimated world-wide total of around 7.1 million (12). There are indications that as of 2007, China had a greater total number of scientists and engineers (13), although anomalies in reported numbers for 2009 make absolute comparisons impossible. Clearly, caveats are in order as to how different nations interpret the definitions of "researcher," but the trends clearly show that the developing world, and especially China, has greater growth rates of science and engineering researchers than the US. In the US and Japan, the number of researchers as a percentage of total employment has been relatively flat (at roughly 1%) for the past decade (14).

The trend is thus that the US is contributing a decreasing share of the global pool of researchers. This is true despite a year-over-year growth rate of US researchers of more than 3%. While the percentage of researchers does not equate to the quality and level of leadership, they do portend greater opportunities for non-US science enterprises.

The Source-Performer matrix for 2012 as provided by Battelle gives a snapshot of the structure of the US funding of research and development, and shows an expected overall growth from 2011 to 2012 (14). Further breakdown of federal funding sources is tracked by the American Association for the Advancement of Science (AAAS), and is shown for the proposed FY2013 budget (15). Note that official budget figures, as reported by the AAAS, report higher federal investments in R&D ($142B in FY2012) (15) than the Battelle estimates ($126B in FY2012), reflecting differences in apportionment of funds to R&D accounts and potential future revisions. Department of Defense funding remains roughly half of all US federally-funded R&D, and is infused throughout each sector. Research in science and technology, as opposed to R&D which includes product development, is also funded by each funding source, and is present in each performer sector, although with different intensities.

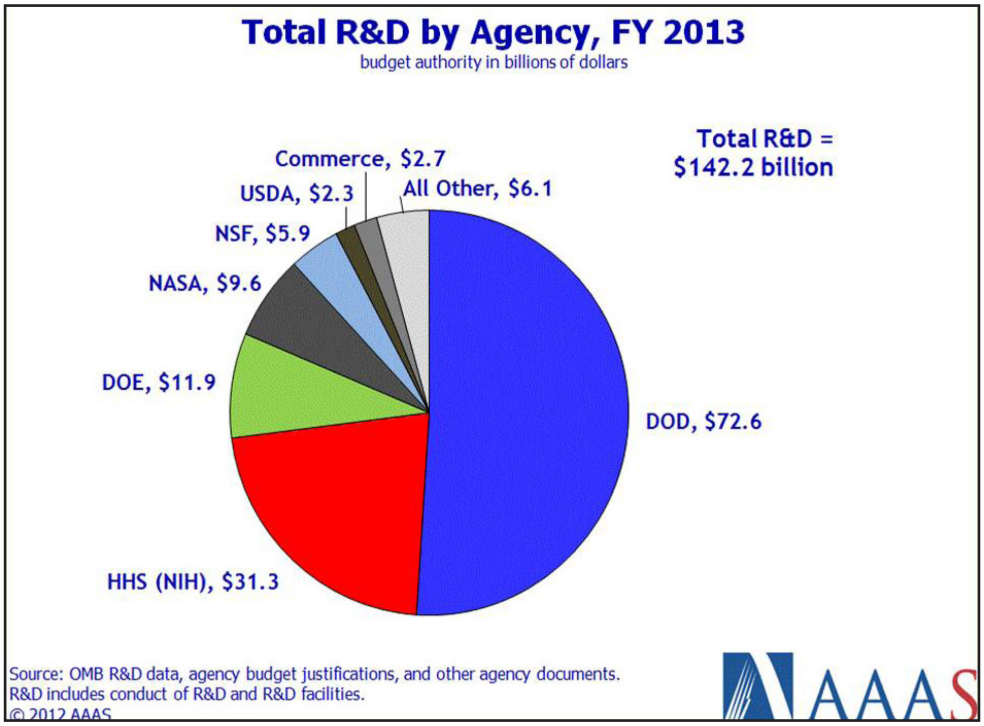


The Source-Performer Matrix
Estimated Distribution of U.S. R&D Funds in 2012
Millions of Current U.S. Dollars (Percent Change from 2011)

Source	Performer					
	Federal Gov't.	FFRDC	Industry	Academia	Non-Profit	Total
Federal Government	$29,152 -2.51%	$14,666 -3.69%	$37,577 -2.42%	$37,440 0.93%	$6,817 -2.29%	$125,652 -1.61%
Industry		$202 2.20%	$273,487 3.37%	$3,868 26.49%	$2,129 8.89%	$279,685 3.75%
Academia				$12,318 2.85%		$12,318 2.85%
Other Government				$3,817 2.72%		$3,817 2.72%
Non-Profit				$3,491 2.70%	$11,055 2.70%	$14,546 2.70%
Total	$29,152 -2.51%	$14,868 -2.36%	$311,063 2.63%	$60,934 2.85%	$20,001 1.55%	$436,018 2.07%

Source: Battelle, *R&D Magazine*

Figure 1. Estimated US investments in Research and Development (R&D) according to source and performer. Reproduced here with permission from Battelle and R&D Magazine (14).



Total R&D by Agency, FY 2013
budget authority in billions of dollars

Source: OMB R&D data, agency budget justifications, and other agency documents.
R&D includes conduct of R&D and R&D facilities.
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Figure 2: Total US R&D investments, by source agency, courtesy of The American Association for the Advancement of Science (AAAS) (15).

The growth in R&D funding masks considerable stress within the research communities of each component performer type. Examination of each stakeholder sector in turn exposes some dynamics and implications of these stresses.

Academia

Among all the R&D performers, the academic community has the highest concentration of researchers pursuing innovative science, and three-quarters of their R&D spending supports basic research (16).[iii] Government-provided grants and grants from industry provide the bulk of the funding sources, totaling around $48B in FY2012, according to the Battelle source-performer matrix. Academia provides around $12B in support to its own R&D, money that comes from tuition receipts, endowments, royalties, and gifts. Since most university faculty are expected to conduct research whether they have research grant funding or not, a certain amount of additional research support is effectively subsidized by university resources.

Despite major increases in National Science Foundation funding and other government funding agencies, there are indications that total output of the academic research enterprise is stalled. The number of refereed conference and journal articles, one of the main observable metrics for research quality, has been dropping in recent years, both in absolute numbers and as a percentage of available publication slots (17). In 2008, there was a slight drop in "triadic patents" (patent filings for a single invention filed in the US, Europe, and Japan) (17). At the same time, there is an exponential increase in foreign competition for publication space, reflecting not just globalization of research, but also dramatic improvements in the quality of research in China, the other BRIC countries (Brazil, Russia, and India), and different nations targeting systematic improvement in their S&T posture, such as Turkey.

The administrative overhead required to conduct government-sponsored research is a significant burden on academic research. A key finding of the recent Defense Science Board (DSB) task force on Basic Research is that "an alarming level of bureaucratic business practices hindering the conduct of basic research … equates to a reduction of the basic research budget" (18). Pre-publication review and restrictions on "deemed exports" of technical information are among many bureaucratic restrictions. The efficiency of government funding for basic research is reduced by the overhead for administration of funds imposed by both government and institutions, and then is further reduced by administrative burdens required of the researchers. The DSB report examined Air Force Office of Scientific Research (AFOSR) funding for basic research, and found that about 60% was made available for intramural and extramural research, with much of the remainder going to institutional withholds (for facilities, administration, etc.) (18). A separate study estimates that 58% of the effort of university faculty funding on federal research projects is actually devoted to research, with the remainder going to research-related administrative tasks (19). The AFOSR case is most likely typical, and thus only around 35% of federal S&T funding is actually expended on research efforts.

One can argue that academic research is even further reduced because a component of the research mission is education. Of course, education of graduate students, postdocs, support staff, and even continuing education of faculty is a worthwhile and necessary function that makes the actual research more productive. It does, however, represent an investment, and when researchers eventually seek opportunities outside of the US, or when they pursue endeavors that do not make use of their science training, it represents a reduction in efficiency.

In certain fields, such as engineering, up to two-thirds of the doctorates awarded are to international students (3). While many end up staying in the US, there is evidence that increasing numbers intend on eventually returning with their expertise to their home country and that in the future, "the world's best and brightest aren't begging to be let into the United States any more" (20). This is a significant and noteworthy new trend, documented by survey data, which supports the notion that large numbers of skilled researchers find opportunities in their home country outside of the US more appealing than remaining in the US (21).

Typical stipends for graduate study in STEM fields (22) provide incentives for US citizens to seek full-time employment before attaining a doctorate, whereas international students are restricted from working during the school year by visa restrictions (23). The result is a vicious circle where stipends and salaries are kept low, due to the availability of large numbers of international participants, while US students are motivated to "bale out" of advanced degree programs early.

Industry S&T

Industrial S&T is especially important to the overall US S&T enterprise. Industry supports R&D from three sources: 1) Contracted R&D for S&T work, 2) Independent R&D (IR&D) that is recoverable from government contracts, and 3) industry-sponsored R&D.

The third component is by far the largest contributor to R&D (at $273B annually, according to the source-performer matrix), although most of that money is devoted to product development, and relatively little goes into fundamental research. The federal government funds the remaining $38B spent on R&D in US industries in the first two categories, mostly through investments by the Department of Defense, mostly in industries that are part of the "Defense Industrial Base."

In the post 9/11 decade, the emphasis of federal funding to the defense industrial base has been on developing tools to help the warfighter in current conflicts. This has naturally led to a greater emphasis on development of products. An even bigger change happened two decades ago in policies affecting IR&D. In the 1992 defense authorization act, companies were allowed 100% cost reimbursement on IR&D expenditures that meet "potential interest to DoD" criteria. Prior to that, IR&D programs negotiated reimbursement levels with a lead service agent. The intention was to give industry greater independence in their choice of research directions; the result was that IR&D decreased, and government visibility into private sector research was greatly reduced (24).

On the other hand, small businesses have been a national asset of scientific research and innovation for decades, and remain so. Small businesses are supported in a variety of ways. The Small Business Innovation Research (SBIR) program began in 1982 and was most recently re-authorized in December 2011 (25). In 2010, the program provided over $1B in funds through a set-aside formula to small businesses. Small businesses are also favored by Defense Advanced Research Projects Agency (DARPA), and venture capitalists (26). However, the pressure for quick results means that often the research and innovation have occurred prior to the investments. Buy-outs of companies provide remuneration for innovative companies, but they often atrophy after they are bought out by larger firms, resulting in an underutilization of accumulated talent. There is some suggestion that coming out of the recession, small technology firms will become increasingly the targets of buy-outs (27).

The larger long-term trend in industrial research has been the demise of regulated corporation research labs. We have seen important research labs essentially disappear or completely change in orientation, such as Bell Labs (28), GTE Labs, and the Microelectronics and Computer Technology Corporation (MCC). As an example, AT&T Bell Laboratories, in its heyday, employed 3500 scientists nation-wide; its successor, the research branch of Alcatel-Lucent, now has about 1000 employees world-wide (29) (30) and is aligned with corporate product needs (31). While the demise of each entity has its own trajectory, the central problem relates to return on investment of research activities. When AT&T was a regulated monopoly, profit accrued on investments in research. For shareholder-owned competitive industries, shorter-term returns are required from comparable investments.

Non-defense companies are increasingly globally outsourcing their research. The globalization of research and improvement in the S&T environment throughout the rest of the world has afforded companies greater opportunities for foreign R&D resources. Microsoft Research, for example, has nine labs in the US and throughout the world, with a recent addition, "Innovation Labs," located in Herzelia, Israel (32). IBM Research maintains laboratories in China, Haifa, India, Tokyo, and Zurich, in addition to their US labs in New York, Almaden, and Austin. Even before they became the new General Motors, GM planned a major advanced technical center in Shanghai, China (33).

Emphasizing the difference between research for future innovation versus R&D, Microsoft Research employs around 1300 scientists worldwide. This represents a small portion of the reported $9B in annual R&D expenditures. Similarly, IBM Research employs around 3000 researchers around the world (34) whereas IBM's reported total R&D budget is around $6B (35) which should support far more than 3000 workers.

Studies have shown that corporate success requires some amount of research and innovation, but that the degree of success is not related to the investment amount in research (36). Perhaps this is because the connection between funded research and product is not uniform, and also because the degree of "innovativeness" of research is not easily quantified nor managed as part of a firm's portfolio. At issue for corporations is the return on investment for their research funding. Because much research is performed as a partnership between government and industry, the incentives for eventual return and the acceptance and management of risk are important investment considerations.

Defense laboratories

The Department of Defense maintains 67 laboratories across 22 states assigned to military services, and is responsible for the employment of over 38,000 scientists and engineers. Their mission is to rapidly develop and transition defense systems to warfighters through knowledge of operational needs and knowledge of developments in the industry and research communities. They also have a mission to provide unbiased technology expertise to the Department of Defense in support of policy development and systems acquisition. As such, the service labs provide a repository of critical S&T knowledge and capabilities, especially for defense needs.

The US government also directly employs scientists and engineers in agencies and activities within the Department of Defense, Department of Energy, and throughout the rest of government. Their functions include management of programs, assessments, and direct research and problem-solving for current projects.

In 2001, the National Academies Press published a severely negative report of the health of government S&T laboratories (37). Noting that it was one in a long string of similar reports (38), it spoke of decreasing numbers of S&T personnel, and negative incentives. The situation may well have improved in the intervening years, and laboratory management has expressed confidence in continuing US technology leadership (39). Recent reports, however, are less conclusive, making recommendations for increased capitalization and continued investment in basic research (40). There is evidence of technology leadership at some of the best research labs (41), and there remain high percentages of personnel with doctorates at a few premier labs. However, many of the 67 labs have low percentages of personnel with PhD's (42),[iv] and relatively ineffective participation with acquisition programs, according to their own summary reports (43). The best scientists often find the working conditions and compensation levels in industry preferable.

Among the issues for the government laboratories, DoD as well as others must be able to adapt to new strategies and directions for national security, energy opportunities, and globalized research. Many of the laboratories were established long ago with specific specializations,[v] which are difficult to evolve as missions and needs change.

Federally-funded research and development centers

In 1940, the "Radiation Laboratory" was established at the Massachusetts Institute of Technology (MIT) with Vannever Bush as the Director, and was a forerunner to the MIT Lincoln Laboratories. They are now one of 39 federally-funded research and development centers (FFRDCs) that collectively conduct research for Defense, Energy, Homeland Security, Transportation, and other US Departments.[v] They are administered by universities and corporations. Ten are sponsored by the Department of Defense (44),[vi] but many others provide services for DoD. Some are better known by their administrative corporations, since they sometimes administer multiple FFRDCs. For example, MITRE Corporation administers three FFRDCs, one for the Office of the Secretary of Defense (OSD), one for Homeland Security, and one for the Department of the Treasury. In 2009, federal obligations to DoD FFRDCs amounted to $1.9B (3)[vii] but federal outlays to all FFRDCs amounted to $9.5B (45). The amount of scientific research varies widely among these institutions.

The FFRDCs assist in transferring technology between the government and the private sector, by promoting development of new technologies. Although controversial in the degree of fairness in competitions with industry and government funding, they provide an important source of employment for scientists and technologists, and a repository for knowledge accessible to the US government and industry unencumbered with conflicts concerning for-profit institutions.

DoD officials have expressed an interest in utilizing the expertise in their FFRDCs to a greater extent (46, 47). However, a push to take greater advantage of FFRDC technical staff risks opposition by for-profit industry (48). As a general observation, at least for DoD FFRDCs, personnel are increasingly called upon to manage and assess other activities, which tend to limit their own innovation contributions and require more administrative expertise.

In a similar way, there are thirteen "University-Affiliated Research Centers," sponsored by DoD, NSA, and NASA. These tend to be more research-oriented, but are otherwise similar to FFRDCs (49). They provide expertise to DoD and other agencies, in public service, independent of profit motive. Often, university faculty will have joint appointments, in addition to research staff affiliated solely with the UARC.

One way to view FFRDCs and UARCs is as a mechanism for connecting scientists and researchers more closely to government needs and issues, to provide added independent advice and counsel in the procurement of technology solutions. This can be rewarding for the researchers, but can also subject them to the pressures of funding, administration, policy issues, and the controversies over degrees of competitiveness.

Connections and transitions

Having surveyed the components of the S&T Enterprise, the interesting activities occur when different components work cooperatively. When industries collaborate with universities, for example, or faculty start small businesses, or government laboratory personnel open the doors to neighboring businesses and university students, transition of ideas and technologies to practical solutions become far more likely.

Government efforts are often focused on fostering deeper connections between groups. The current administration has certainly followed this pattern, emphasizing new interdisciplinary and interagency research endeavors. The Multi-University Research Initiative (MURI) program, for example, funds roughly 190 different multi-university research consortia (50). Recently, program reviews for the entire program have been held in conjunction with industry conferences, permitting industry to participate in the reviews. The National Network for Manufacturing Innovation (NNMI) intends on establishing up to 15 regional consortia for research in manufacturing, combining academia, government, and industry (51). The Department of Defense has established a "Defense Innovation Marketplace" to better connect Industry with government, to allow industry to market research results to select government reviewers, and to disseminate information to industry (52). Individual States are particularly active in establishing incubators for innovation. For example, New York State has the "Centers of Excellence" program with six multi-party research centers connecting the State, academia, private venture capital companies, and other private sector entities (53).

Such efforts are worthwhile and laudable. However, they involve cooperation among components with different cultures that would normally prefer to stay within lanes. There are typically difficult issues over intellectual property rights, and the default is to undervalue the contributors to innovation. Countries around the world are struggling with the university-industry relationship, and how to appropriately remunerate for the intellectual property and risk inherent in innovation (54).

The evidence concerning S&T trends

Is the US enterprise in science and technology still the leading the world? What is the evidence concerning trends in science and technology output?

The field of scientometrics is about measuring the quantity and quality of scientific research. While it mostly tracks academic output and the publications of corporate R&D centers that choose to make information public, it can provide a harbinger of trends within countries. Other scientometric studies turn to statistics concerning patents, since they can reflect research activities in industry. Here, we integrate assessments[viii] to provide our own interpretation of trends in S&T quantity and quality.

The assessments generally agree that China is experiencing exponential increase in its quantity, and its quality, of S&T output (55). These studies mostly look at English-language refereed publications, but Chinese-language production is also expanding. The Wanfang database of Chinese academic publications in Chinese language journals, conferences, and dissertations, contains more than 14 million articles (as of July 2008) (56). While the US has a number of efforts that scout and assess foreign S&T developments, and perform frequent "net assessments" and technical exchanges as part of the Technical Cooperation Program (57), the techniques used to perform these studies are themselves the topics of research efforts, and such scouting is inevitably relatively narrow. Innovation is difficult enough to recognize when it occurs in one's own domain. Accordingly, it is likely that there are innovations and high quality research among the large and rapidly increasing body of S&T output in China. As an example, the US-China Economic and Security Review Commission reports that in at least some certain modern military systems developed by the Chinese, the US underestimated the capabilities and rate of progress of the Chinese military-industrial base, and that this underestimation was in part related to a failure to take into account China’s increased investments in science and technology (58). Asia more generally is also increasing its quantity of S&T output. Taken together, the Asian nations including China and Japan produced nearly as many top-quality refereed journal articles as the US in 2009, the last year for which data is available.

Apart from China, the other BRIC nations appear to be focusing on increasing research output, albeit they remain far below US production levels.

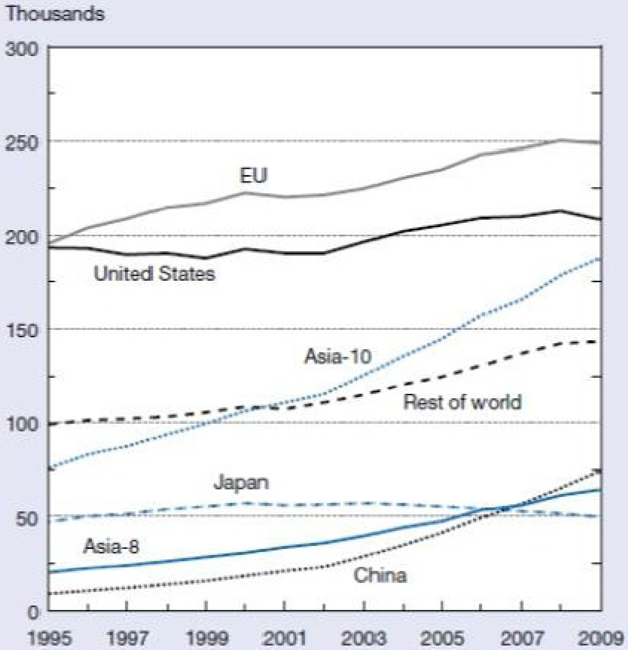
There is evidence that US S&T output is decreasing, although there are various possible explanations, and the rate of decrease is small (59). It is certain that the proportion of US output to global S&T is declining, largely due to the increase in non-US output.

There is general agreement that the US retains the most innovative work, albeit China and others are improving. The US has the best infrastructure for converting S&T results to entrepreneurial businesses, but continues to lose out when it comes to manufacturing commodity products. There are questions as to whether American imaginations are as captivated by science, and by “big ideas,” as they were in the past (60).

EU-25 is doing very well in total S&T output, comparable or even above US output. Their quality is also high (61). To the extent that the US retains leadership in S&T fields over the EU, it is because scientists often migrate to US facilities, and because the US does a better job at transition.

Figure O-13

S&E journal articles produced, by selected region/country: 1995–2009



Asia-8 = India, Indonesia, Malaysia, Philippines, Singapore, South Korea, Taiwan, Thailand; Asia-10 = Asia-8 plus China and Japan; EU = European Union

SOURCES: National Science Foundation, National Center for Science and Engineering Statistics, special tabulations (2011) of Thomson-Reuters, Science and Social Sciences Citation Indexes, http://thomsonreuters.com/products_services/science/, and The Patent Board™.

Science and Engineering Indicators 2012

Figure 3: National Science Board. 2012 Science and Engineering Indicators, Figure 0-13. Production rate of journal articles for select countries and regions. Courtesy: National Science Foundation (59).

Ronald Kostoff points out that if one discounts biomedical research, then in certain fields China’s output is already greater than US total output, such as in nanotechnology (59). In Kostoff’s figure (Figure 4), Kostoff uses databases with relatively fewer biomedical entries, and compares them to the Science Citation Index (SCI) database, which is relatively heavy in biomedical references. Since the metrics are based on looking at publication counts in high-caliber refereed journals and conferences, and since there are a limited number of such slots available, the suggestion is that the quality is comparable. Similar trends are seen in counts of citations of nanotechnology articles, and citation indices are most likely a lagging indicator, since, as reported elsewhere, “it will take some time before the international academic community cites scientific papers from emerging countries to the same extent they reference publications from traditional leaders (62).”

The situation in the field of nanotechnology is illustrative. Based on pure scientometric analyses, China has made tremendous progress in nanotechnology output, and has a greater rate of journal publications than the United States (63). However, based on citations, presence in the top three high quality journals, and the level of patents, the studies conclude that China still has a long ways to catch up in terms of quality of research. For example, the research forefront, such as that represented by “DNA

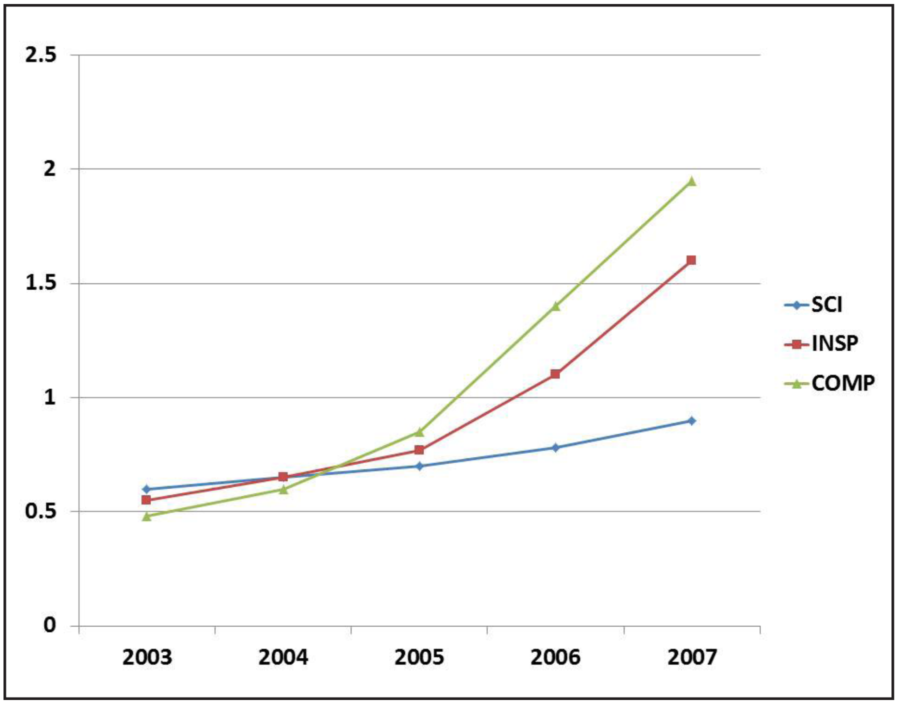


Figure 4: The ratio of Chinese papers to US papers included in specific databases. Modified with permission from Kostoff, "Comparison of China/USA science and technology performance," Journal of Informetrics *(2008), showing that recent Chinese production of papers as listed in the INSPEC (INSP) and Ei Compendix (COMP) databases, which contain relatively fewer biomedical papers compared to the SCI database, is relatively larger than US production of papers included in those databases.*

nanotechnology," was invented in the US, and is maturing to the point of potential applications (64). So we continue to see US dominance in the field, but contributions from China, and the rest of the world, are rapidly increasing.

As another example, reports from scouting missions to Chinese universities and reviewers of conference papers submitted to an international conference on Artificial Intelligence (AI) express admiration for the quality and quantity of research in AI led by Chinese researchers. However, the statistics and assessment is that AI as a field is still dominated by US scientists.

Taken together, there is no direct evidence that the US has been overtaken in quality of S&T output, and most indications support the notion that the US leads the world in science and technology in all fields. However, the trends are not favorable to maintenance of this position, and it seems likely that in some fields, US leadership could falter. When such cross-over might occur, or in what fields, and whether it is inevitable, is uncertain.

DoD policy implications

While a gradual decline in US S&T leadership does not provide a "Sputnik moment" (65),[ix] it poses no less of an existential threat. When technical innovations occur in potentially adversarial countries or domains, a strategy that relies on technological superiority for defense capabilities will no longer suffice. If a potential adversary can introduce a disruptive technological capability, they can then use deterrence or influence to control behaviors, compete economically, secure scarce resources, and control diplomatic agendas.[x] The US strategy continues to depend on technological superiority.

Thus from a DoD perspective, it is imperative that the US maintain its position of technological leadership. A Senate Armed Services Committee (subcommittee on Emerging Threats and Capabilities) hearing on the "Health and Status of the Defense Industrial Base and its S&T-related elements" (66)[xi] took place in May 2011, and highlighted some of the issues and potential solution paths. Those testifying called for a comprehensive strategy for the US to maintain technological leadership well into the 21st century. Many other specific suggestions were made during that hearing as to ways to support the industrial base and to assist the partnership of DoD and the defense industrial base to utilize technology advances efficiently.

Future prospects

Many remedies have been proposed to ensure continued US technology leadership, in the face of challenges and stresses within the US S&T enterprise. Some of the typical concerns are overall funding levels, DoD funding for

S&T, the efficiency of the application of funds to S&T, and the emphasis of disciplines within S&T. Other concerns include regulations and impediments to research in S&T, and the production rate of scientists and the career opportunities. We have noted many of these issues in our survey of elements of the S&T enterprise.

The larger concern is over the respect in which science and technology is held within our society. Since research is an intermediate product, often accomplished years before product and societal benefits, there is often little appreciation of the role of the researcher and inventor. After World War II, there was great respect afforded scientists, particularly physicists. Post-Sputnik, there was a deliberate effort to elevate the stature of science and technology, and the manned space program certainly contributed to societal respect.

Some argue that it is because there has been a precipitous off-shoring of manufacturing that the generation of new ideas has moved overseas (67). Andy Grove of Intel makes a complementary argument: That as manufacturing moves overseas, American companies lose the knowledge of how to scale up new ideas to full-scale production (68). Both arguments suggest there are reduced incentives for domestic research as manufacturing moves elsewhere, and lead to the conclusion that research is best performed by those with familiarity of product production. Thus, they argue that we need to reinvigorate manufacturing and production for economic vitality so that technology development and leadership will follow.

And, indeed, the nation has an Advanced Manufacturing Initiative, and many cite a resurgence of domestic manufacturing as incentives normalize to less favor off-shoring.

Summing up the landscape

The US has the best universities, the most winners of the Nobel Prize, the best young scientists, and the largest investment in research and development of any nation on earth. So how can it be that the US is apparently losing its lead in science and technology? The answer isn't that the US has slowed down, although according to some the rate of technical progress has, indeed, slowed. The fact is that the competition has discovered the importance of innovation, and has begun to reap rewards from speeding up. We have seen that China especially is mustering its considerable resources to develop what they call an "innovation economy," but that other nations, as well as Europe, highly value science and engineering, and implicitly or tacitly have begun to challenge US technology leadership. At the same time, the globalization of research and ease with which international science collaborations take place mean that continued US leadership requires full engagement with the international scientific community. Thus, impediments to exchange of information and bureaucracy in the conduct of US research are counter-productive.

According to Bill Gates, you always have to renew your lead.[xii] The US has the resources and infrastructure necessary to maintain and renew a lead in technology. But momentum is not sufficient. In light of concerted efforts in other nations, coasting in science and technology will jeopardize national security, and also jeopardize the economic and societal benefits of being first to market with technological innovations. No single agency or entity within the United States can enact a strategy to renew the technology lead. Instead, continued US technical leadership will require a dedicated and coordinated effort throughout the society.

Part B: Technology Goalposts for the 21st Century: Grand Challenges

The need for Goalposts

We have seen that the United States leads the world in scientific and technology talent, and that the US supports more research than any other nation, and by any measure of creativity and innovation, its scientists, technologists, young researchers, and seasoned lab personnel are more productive and more knowledgeable than researchers elsewhere in the world (14). However, notable high-profile accomplishments of this extraordinary pool of talent have become, at least seemingly, infrequent.

We have further discussed how others have begun to emulate American investments in science and technology, and how globalization of R&D increases the importance of innovation, since innovation enables "first to market," and the ability to field applications before others. The key is the conversion of ideas into capabilities and applications, which generally requires specific goalposts and determination to reach those goals.

25 May 1961

A little more than fifty years ago, President John F. Kennedy confronted a dangerous and complicated environment with mounting security challenges around the globe and a nation that had recently suffered a recession. And yet, he saw opportunities. Kennedy said: “The first and basic task confronting this nation this year was to turn recession into recovery.” (69)

He continued however: “But the task of abating unemployment and achieving a full use of our resources does remain a serious challenge for us all. Large-scale unemployment during a recession is bad enough, but large-scale unemployment during a period of prosperity would be intolerable.” (69)

The speech that President Kennedy gave on 25 May 1961 is remembered as his announcement of a national challenge: That the nation should “commit itself to achieving the goal, before the decade is out, of landing a man on the moon and returning him safely to the earth.” He understood the impact that such a decision would have on the imagination of scientists as well as the rest of the nation. He said that “I believe we possess all the resources and talents necessary,” but that we had “never specified long-range goals on an urgent time schedule” in order to marshal “the national resources required for such leadership.” (69)

And that is the situation today as well. With the need to fashion a faster economic recovery, the US needs to create new business opportunities, new fields of endeavors, and establish technological leadership, to restore the ability to manufacture goods that people everywhere want and need, and to lead the world in innovation in the development of new sources of energy, to provide new and compelling products in medicine, transportation, environment stewardship, and information technology. And just like fifty years ago, focusing our efforts on specific science and technology goals can be an integral part of taking that step forward as a people.

Notably, Kennedy set a specific goal that required science and engineering advances. While much debate ensued as to the feasibility of the goal, Kennedy had sought assurance in advance that the goal might be achievable. The manned mission to the moon became “big science,” but involved basic science, infrastructure, and engineering advances, and became a way to challenge American entrepreneurship to innovations in many different fields and endeavors. And, importantly, it helped bring America to technical dominance in space applications, both manned and unmanned.

America has historically understood the importance of science and technological leadership. For example, in the Second World War, US scientists and engineers created technical capabilities and the nation mobilized a manufacturing base to lead us out of a world at war. In fact, Vannevar Bush recognized the opportunity that the “federal government should accept new responsibilities for promoting the creation of new scientific knowledge and the development of scientific talent in our youth”. He also recognized that the result would “stimulate new enterprises, provide jobs for our returning servicemen and other workers, and make possible great strides for the improvement of the national well-being.” (69)

Ever since, the US has supported an enterprise of scientists and engineers, in the Department of Defense, and across the whole of Government with this mission. Much of the research is exploratory. Some is applied, to make advances in particular domains. And from time to time, the US has focused on particular goals, as Kennedy announced fifty years ago.

In these complex times, a single “big science” program is not the appropriate way to muster the technical resources of the nation for the greatest benefit. Instead, we believe that a variety of specific application challenges provides the appropriate way to inspire innovation and productivity in our utilization of national technical talent.

New challenges

It is time that we challenge the research and engineering community to take “longer strides,” as Kennedy said in 1961 (69).[xiii] Rather than a “big science” goal, it is our opinion that the community should set a “clear leading role” in each of many domains. Whereas in 1961 Kennedy saw space as possibly holding the key to our future on earth, we now believe that domains such as medicine, energy production, clean environment, transportation, manufacturing, and education—these in combination hold the keys to our economic and security future.

Rather than expecting scientists to continue to make incremental progress in the body of knowledge in each of these domains, we believe that technical leadership demands that a certain amount of research and engineering be focused on specific application challenges, to achieve grand accomplishments for the betterment of mankind, with specific goals in domains of human endeavors. As President Kennedy said back then, the decision to under-

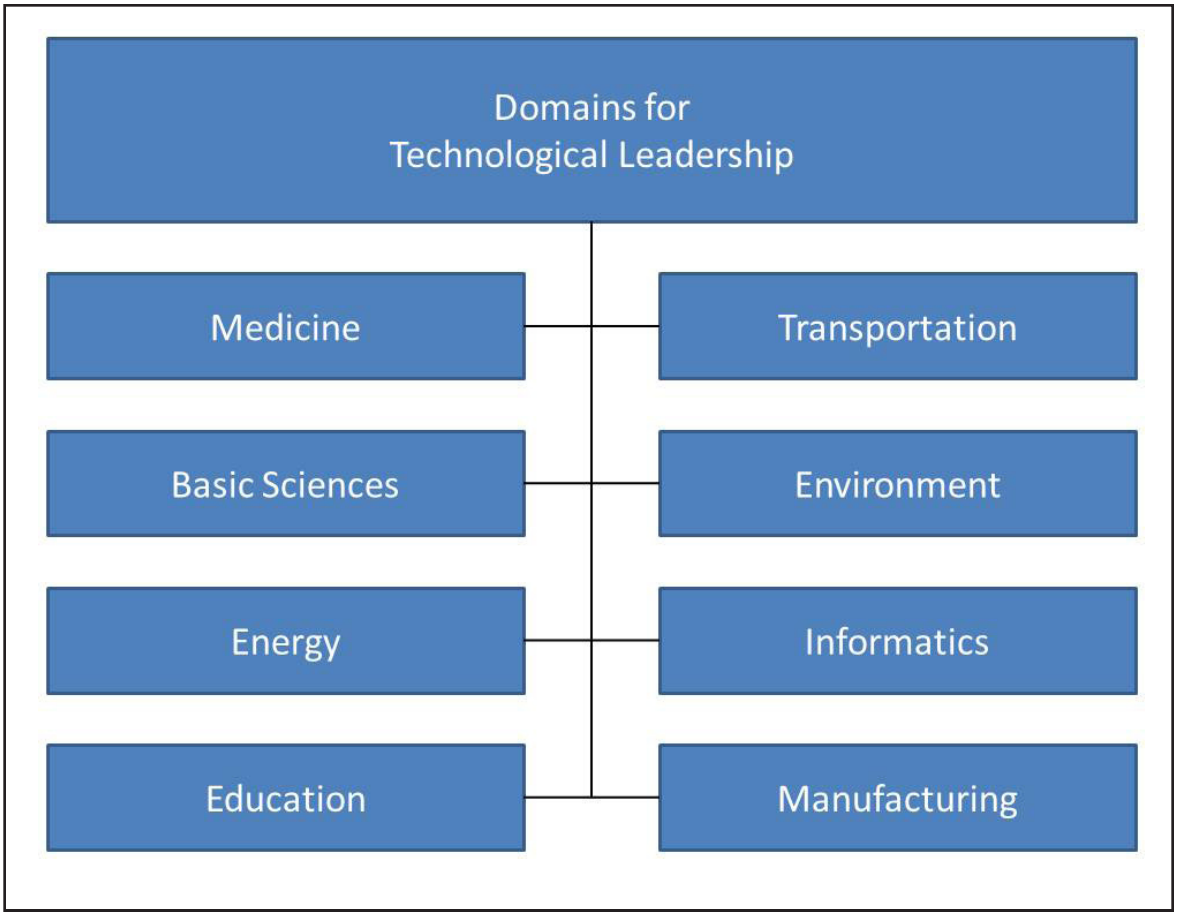


Figure 5: Domains for potential Technology Goalposts.

take these challenges "demands a major national commitment of scientific and technical manpower, material and facilities, and the possibility of their diversion from other important activities where they are already thinly spread. It means a degree of dedication, organization and discipline which have not always characterized our research and development efforts." (69)

The challenges that we outline here would give a purpose and direction to our scientific endeavors, and open new frontiers for America and the world. We might not achieve all of them. We might achieve goals different than the ones we set out to achieve. Some goals might be achievable within this decade, and others might require multiple decades. But these are goals that we can all agree are worthy of a great nation, that can enable our economic recovery to lead to prosperity with new businesses, new jobs, and new benefits for all.

Our challenge is to pursue radical new opportunities, to open new frontiers by the end of this decade, with seminal and very specific breakthroughs in each of the following disciplines: Medicine, Transportation, Energy, Education, Environmental Science, Manufacturing, and Information Access.

Medicine

Steady progress continues to be made in the areas of medical diagnostics and therapeutics for specific diseases. We can be proud of the contributions of our nation's robust biomedical research enterprise, which harnesses top talent in academia, industry, and government institutes like the National Institutes of Health (NIH). However, our medical research and healthcare delivery capabilities are poised for tremendous improvements, renewed global leadership, and—perhaps most importantly—reduced costs, by the end of the decade. In the past, the Nation has challenged medical scientists to "find a cure for cancer," or to "focus research on cell-based technologies." These and other challenges are laudable. Our goal, which is assuredly achievable, is to call on our medical research community to leverage information processing, progress from the Human Genome project, and progress from the past Decade of the Brain and subsequent neuroscience advances, to result in more effective and cost-effective "personalized" medicine and a revolution in medical knowledge.

Digital medical data

One of the most significant opportunities we face in the medical domain is the continued development and widespread employment of information technology to digitally collect and store medical data. The prospect of revolutionizing the way medical data is stored may lead to paradigm shifts in diagnosis and patient care—as well as our analysis of "what works" in medicine, and what doesn't.

The Human Genome project, together with advances in automated sequencing, has given us an ability to understand the commonalities and differences in the human genome. By leveraging this capability, we stand on the brink of generating powerful genetic environmental correlations to aid in risk factor and predisposition assessment and therapeutics for many diseases, particularly cancers.

The scientific community should be challenged to develop affordable, reliable, and secure methods of sequencing, storing, and sharing individual genomes and related patient histories and health data. We envision private companies maintaining that information—encrypted, secure, and anonymized in such a way that the information can be used in comprehensive statistical analyses without infringing on the rights and liberties of individual Americans. These statistics and information, when combined and analyzed across populations, can form the basis for implicit clinical studies, to understand causes of diseases and conditions, and to better understand what interventions work and under what conditions. Better knowledge can produce better outcomes, at far less cost and with far greater efficiency. The knowledge comes about from collecting data, and using advanced information processing capabilities to analyze and interpret that data. We have the computing power, and much of the necessary diagnostic technology. We need to focus on collecting and analyzing digital medical data through private enterprises to improve medicine and medical practices while reducing our spending on less effective treatments.

Neuroscience approaches to medical care

One of the most intensive areas of research in medicine and biology has been the work of our neuroscience community. Over the last two decades, tens of thousands of researchers have made enormous progress in our understanding of the function of the human brain. And while many mysteries remain, such research has enabled novel insights to neurological diseases and psychiatric disorders.

We now understand with greater clarity the effects of both physical and emotional trauma on the structure and function of the brain. Traumatic brain injuries (TBI) and post-traumatic stress disease (PTSD) have been devastating to our soldiers and marines who have been afflicted with these disorders, and to their families that share in the psychological, social and economic burdens that these disorders incur (70). We are now prepared to use the knowledge garnered in and through neuroscience research to develop new and innovative treatments, in ways that best employ newly formulated drugs that target key brain areas and produce less problematic side effects, and technologies that allow more effective diagnosis and the ability to directly engage specific pathways and regions of the brain (71).

These approaches would greatly benefit our military wounded, to whom we owe our best science and best approaches, but also help all those in our society who suffer the ravages of neurological and mental illness. Pain and addiction to pain-relieving drugs cause untold problems: We can challenge our neuroscientists and medical science communities to develop effective and efficient treatments to more effectively relieve pain and prevent and treat addictions. Degenerative neurological diseases can rob both the elderly and middle aged adults of their abilities and independence. Anxiety, depression, schizophrenia, and other psychiatric disorders can rob the young, adult and elderly of quality of life. We should now harness our newfound understanding of the brain and advance neuroscientific discoveries, along with data that can be gathered using modern information technology, into medical care, so that the this decade will be one of meaningful medical accomplishment over neurological conditions, and so that we may treat the scourge of neurological and psychiatric illness in efficient ways that reduce overall costs, and provide the level of care and quality of life that is the right of every one of our citizens.

Transportation

Our economy depends on the movement of goods and services. With increasingly rapid information exchange, we often forget that there is still vast movement of physical goods and people, including interstate travel, and intrastate commuting, by rail, air, waterways, and of course, highways. Transportation arteries are the lifeblood of the Nation's economy (72). Imagine if commuting to work, or the transporting of goods across the country, could be done autonomously: the ultimate in mass transit, without drivers, on individual's schedules.

The Department of Transportation has long explored the possibility of "smart roads" that can take over the navigation of vehicles, provided that the vehicles are suitably "smart" themselves, providing greater safety, and relieving the need to actually drive the vehicle (73). This is possible because the road knows where all the vehicles are located, and can safely steer each vehicle to avoid collisions, maintain constant speed, and assist vehicles to enter and exit the smart road efficiently. When the vehicle leaves the smart road, the driver is alerted and takes over the navigation, as with a normal vehicle. With our interstate system having served the nation and enabled efficiencies in commerce for the past 50-plus years, it is time to consider technological innovations that take the transportation opportunities to the next level.

New "smart traffic lights" are beginning to emerge and may reduce traffic waiting time by 30% (74). The extension to smart roads could significantly reduce our 168 million gallon annual fuel consumption (75).

Smart road technology could help to dramatically reduce the number of automobile collision-related deaths in the United States—the sixth leading cause of preventable death in the nation. In 2006, nearly 43,000 Americans lost their lives in road traffic accidents and 3.3 million were injured (76). Smart roads could be a primary enabler for new businesses and improved business efficiencies, with added safety. Automated cargo delivery between fixed transit nodes might become commonplace, making our interstate highways into efficient containerized shipping routes. Personal commuting could become more like private rail car transportation, freeing drivers to do other productive work in their smart car while transiting on major highways.

But even more is possible. Recent progress in the development of fully autonomous vehicles (77)—driverless systems that can safely navigate in traffic on major routes and even in urban environments—could enable automated systems for the delivery of cargo, and perhaps even fleets of autonomous vehicles that can provide transport for people. We can envision cars and vehicles that are safe and easy to use: You set the destination, and the vehicle takes you there. With sensor systems and communication devices, the vehicles are able to navigate safely, with no collisions, and with uniform efficient velocities. Traffic jams and delays could become a thing of the past.

For long-distance commuting, we have long dreamed of efficient high-speed rail system. But the high cost of the infrastructure, and the size of our vast country, has inhibited the development of a large network of trains that might enable us to commute at hundreds of miles per hour between major urban centers. The science and engineering communities should be able to develop less expensive and safe alternatives to high speed rail systems. Ideally, one would enter a car that would autonomously and independently accelerate to join a train that efficiently combines many cars on a trunk line (78) traveling at high speed, until cars independently depart from the train to permit disembarkment at siderail stops. We don't know whether the technology will involve magnetic levitation on special tracks, or simply high speed bus systems on dedicated median lanes, but progress in the efficiency and understanding of transportation systems makes it feasible to consider vast networks of affordable and flexible high-speed ground transportation systems.

Energy

In 2008, the United States produced roughly 15% of the energy in the world, and consumed 20% of the total amount of energy produced everywhere (79). The availability of cheap and plentiful energy has, historically, empowered the nation to build factories, give transportation freedom to our people, and maintain comfortable homes. Against a backdrop of increasing energy imports and prices that we don't control on our own, we need to find new sources of affordable and plentiful energy, both by using what we have now efficiently, and by using technology to increase the availability of new sources. Recent progress in the extraction of natural gas through hydraulic fracturing may change the balance, but presents new opportunities as well as challenges.

Much of our imports of oil and gas are used for our transportation needs. However, with the increasing prevalence of plug-in cars and electric vehicles, we can envision replacing our imports that are used for transportation to indigenous sources that use renewable resources. There is much work being conducted on renewable sources, from bio-fuels, to wind energy, to tidal waves and algae systems. Major progress has been made in the conversion of grasses and woody material (cellulosic conversion) (80) to transportable clean fuels. How can we bring these many renewable concepts to fruition? An achievable challenge for scientists working on renewable energy is to develop systems to generate sufficient electrical power for transportation purposes to replace non-American foreign imports of oil and natural gas.[xiv] In this way, Americans would be free from high gasoline prices, and can enjoy affordable transportation using energy that does not deplete earth's petroleum resources.

As our transportation systems migrate to dependence on the electrical grid, we should move quickly to implement smart grid technologies for our entire electricity network. Smart grids assist in balancing loads, and assist customers in scheduling their energy demands, to greatly increase the efficiency and reduce the overall costs of both the infrastructure and the production of energy. The reservoirs of batteries in electric vehicles, plugged into home outlets and outlets at workplaces across America, can contribute to this smart grid as active elements in both the supply and demand for energy.

While we are reducing our transportation costs, we should develop technologies that enable homes to be self-sustained, by generating sufficient energy from local sources to provide for the heating, cooling, lighting, and other needs, and to supply electric power for the basic transportation needs of battery-equipped vehicles associated with the home (81).

We will need new trunk lines for the distribution of electric power from production sites into our urban centers and throughout the nation, and to the factories and businesses that will enrich our nation in the future. With advances in the technologies of electricity transport, to include superconductivity, we can now call on our scientists and engineers to develop new and affordable energy distribution systems (82).

Many have been critical of alternative energy sources, saying that they can't possibly replace the vast energy resources of the oil and gas supplies located in concentrated pockets throughout the world. Of course, we have seen that petroleum supplies are increasingly difficult to extract, and in any case, it is time to scale up concepts for alternative sources to provide large amounts of energy to power not just our nation's current needs, but to enable new businesses and new energy-intensive production activities in the future. To this end, there are safe and clean energy possibilities, which our technological leadership could exploit. Even nuclear energy, for which we have recently had reminders of the dangers, can be made far safer through technological advances; for example, small liquid thorium reactors have been suggested as potential alternatives with certain advantages in terms of safety and weapons diversion resistance (83).

Perhaps the most ambitious approach to large energy supply, the longest stride, combines our experience in space activities, and building space stations, with solar cells and energy transmission. Concepts involving vast solar arrays parked in space, transmitting power in narrow beams to isolated receiving stations, for distribution to consumers, have been explored for years (84). It is time to develop demonstration systems, and to consider production systems, able to supply power for our transportation, home, and industry needs.

Education

Education underpins our entire economy. Presidents often extol the importance of education for "winning the future" (85). In an ever more globalized economy with advances in science and technology at the heart of economic change, an educated American populace is increasingly essential to our continued prosperity. To ensure an educated workforce that will be able to compete in the global marketplace, the US would do well to capitalize on two trends in the field of education: an increased adoption of education technologies and an expanded emphasis on effective and inexpensive means of delivering lifelong learning opportunities so Americans can more rapidly adapt their skills and knowledge in response to shifts in occupational demands.

Our technologists should now research and implement new ways to train people, especially into new career fields, through technology-rich teaching methods (86). We might increase our use of virtual environments, and 3D environments; we might increase our use of competition and productivity enhancements. Information technology can help us collect data, and good data can help us understand teaching methods that work well. While we should never disregard the importance of a good and inspirational teacher, we can help teachers perform their best by empowering them with the best and most productive teaching aids. In fact, our improved understanding of neuroscience, and how people actually learn, can help us develop methods for helping people to learn faster, and retain more, so that they can take on new activities, and new careers, throughout their lives, without requiring years of retraining and apprenticeships before reaching their full productive capacity.

To make truly great strides, however, we would like to achieve "language independence" for efficient and accurate means of verbal and written language translation, from any language into English, and English into any other language (87). This dream, seen in science fiction, is now much closer to reality, thanks to powerful computer technology and new theories of ways that machines can learn from large databases of examples (88). Language independence would greatly improve our ability to teach, learn, and assimilate information from around the world.

And while we consider increasing our use of technology in education, we understand the current limitations of computer learning, and indeed, all interactions with computers. Our interfaces to computers currently require that we learn how to use certain interface devices, which is not hard, but we also need to learn how to use applications. Technologists should now speed the process of making interfaces with computers more intuitive, more natural, and more like our interactions with people.[xv] With recent accomplishments, we are in the early stages of developing computers that "learn their users." Such approaches will open entirely new opportunities for social computing and developing computer–based tutors that augment and mentor students across a broad range of topics.

Environment

In 1972, the US Congress passed the Clean Water Act which has resulted in far cleaner rivers and streams, and greatly improved American accessibility to clean sources of fresh water. However, the global need for fresh water continues to grow, for agriculture, for industry, and for people. Many places in the world, including our own Southwest, face increasing constraints based on the availability of clean water, especially as ground water sources are tapped and depleted (89). Technologists have made tremendous progress in making small portable affordable water purification systems readily available, for example advances in water purification systems (90, 91) inspired by earlier DARPA projects (92). It is time to increase the scale of these efforts, to develop technologies that can increase the availability of clean water world-wide, for agriculture, for industry, and for human consumption.[xvi] Whether through desalination, water purification, or nanotechnology for treatment facilities, abundant clean water would open new possibilities for the world.

Clean energy supplies are also an important aspect of our stewardship of the environment. While we have already addressed concepts for developing alternative energy sources, technologists have long considered dramatic ways to clean up many of our existing energy sources. Perhaps technology can not only scrub particulate matter from our coal-burning power plants, but can find ways of transforming coal in a way that pollutants and carbon dioxide can be trapped and sequestered. Perhaps new catalysts or other technologies can be used to further clean the effluents of our transportation systems and our factories. Perhaps we can develop a clean alternative fuel for every type of transport (93).[xvii]

Many now believe that the future of materials lie in nanotechnology, and the use of nanotechnology to manufacture new kinds of materials. The nanotechnology community should now focus on degradation and substitution issues: to develop bioplastics and to implement their widespread use, and biodegradable materials, or other materials that can replace petroleum-based plastics, which would be easier on the environment, and enable opportunities for new applications and new businesses.

Manufacturing

With the economic recovery, we have seen some resurgence in US manufacturing, to include the automobile companies returning to stability. However, to truly restore manufacturing as a primary driver of the American economy, new high-technology methods for production of goods need to be adopted in order that we compete globally in this important sector for the creation of businesses and opportunities.

Our scientists involved in Systems Engineering, design, and manufacture of the complex products and systems purchased by consumers (and governments) have long experimented with novel productivity enhancements. Computer-aided design, modeling and simulation, virtual testing, and adaptation through software upgrades have all shown promise to improve our production of goods and systems.

We need to institutionalize these techniques, and to take the next leap to provide for novel manufacturing capabilities wherein we lead the world in our ability to produce parts and systems. In particular, in the same way that laser printers have revolutionized our ability to print and exchange text and drawings on paper, we need to have 3D printers that can, on demand, generate useful workable parts and products. We have seen already 3D printers that produce plastic models and objects (94);[xviii] we should now develop affordable devices that can use additive manufacaturing parts made of metal and other materials, to reduce the need for warehouses of pre-manufactured parts, and to solve complex logistic trains. In this way, warehouses can become digital, and designs manipulated and perfected using virtual design software, as opposed to physical models and reworked prototypes. We can envision libraries of digital parts, licensed when implemented and manufactured in systems. With on-demand manufacturing, costs are reduced, and systems become more adaptable and resilient.

Going one step further, we should have customized manufacturing, wherein articles are made for the individual person. We are approaching the time when scanners and manufacturing systems should be able to design and produce clothes, shoes, and other products to precise specifications, customized per the needs and desires of the individual. New efficient businesses of producing individualized products, not just apparel, for consumers should be possible using customized, on-demand manufacturing.

To underscore our ability to provide for a resurgence of manufacturing as a new and advanced capability, with new kinds of products and businesses, as a nation we should focus demonstrations on a particular locale, or a couple of urban centers, where the new businesses would have great impact, and where consumers could benefit most directly. We might, for example, set up demonstration on-demand manufacturing capabilities in Detroit and New Orleans.

Informatics: Ubiquitous Information

From the founding of the ancient Library of Alexandria to the invention of the printing press and the development of the Internet, the ability to store, access, and disseminate information has proven essential to advancing human knowledge and expanding the number of people who benefit from that knowledge.

Over the centuries, mankind has shaped a communications revolution, transforming a world where information exchange across considerable distances was both expensive and rare into today's paradigm where long-distance communication—in multiple forms—has become commonplace. Still, we have not yet reached the apex of human communication. The next step in the migration toward increasingly broad access to comprehensive information is to universalize the Internet, making it available to all humans on the planet at a negligible cost. An ability to telecommute, interact with fellow workers wherever they are, and share information and ideas with others freely without restrictions would enable dramatic new opportunities in business and industry that would promulgate to every corner of the nation, and indeed globally.

Though access to the Internet continues to expand rapidly across the globe, the ultimate realization of this goal will require research efforts to develop more cost-efficient information-delivery techniques, followed by sustained investment in this technology and establishment of new infrastructure. This project might involve networks of satellites (perhaps influenced by microsatellites), or new wireless communication protocols and the concomitant development of more affordable portable personal communication devices.[xix]

Basic science

In 1945, Vannevar Bush—then the President's Director of Scientific Research and Development—outlined a vision for US scientific research activities in the post-war period. In his report, entitled "Science: The Endless Frontier" (1), Bush laid out the importance of basic research to the Nation's science research enterprise. Basic research—though "performed without thought of practical ends"—was the "pacemaker of technological progress," and "created the fund from which the practical applications of knowledge must be drawn." Bush further argued that the "simplest and most effective way" that Government resources could be brought to the service of the nation's industrial research endeavors would be to "to support basic research and to develop scientific talent." With this vision, Bush's "Endless Frontier" resulted in the establishment of the Office of Naval Research, the National

Science Foundation, and, later, the National Institutes of Health, the Defense Advanced Research Projects Agency, and NASA—as well as a robust national program of basic research at universities, research centers, laboratories, and institutes and a quadrupling of the number of research scientists dedicated to fundamental science in just a few decades (95). Semiconductors, microelectronics, medical diagnostic technologies CT and MRI, and key developments in computer science all emerged from basic science developments in the post-war period. In short order, American science and engineering advances became the envy of the world and gave rise to technical resources and capabilities that fueled unparalleled economic success.

Other nations around the globe aspire to similar economic advances, and are investing heavily in science and the application of science to new technologies and capabilities. China, for example, has launched an effort to become an "innovative nation" by 2020 and a global scientific power by 2050 (96), and has reserved 15% of its science and technology investment for the 973 program that funds basic research (97).

Extending the American S&T-driven economic boom will require continued and enhanced American leadership in basic and applied science. For American technological progress to remain at the forefront, we will need to foster more effective and integrative relationships between the basic research community and applied researchers, to decrease the time in which fundamental science discoveries are translated into practical technologies. We need to re-infuse our research communities with the characteristically American spirit of competitiveness to drive our success in a more competitive age.

American leadership in the 21st Century requires that American scientists strongly participate in basic research, and stay current with a body of basic science in a globalized research environment. Leadership also requires that we facilitate and expedite the creation of practical applications and knowledge from the fund of basic science. Being first to codify and utilize basic science is more important than being alone in possession of the fund.

Accordingly, we need to challenge (and incentivize) our basic science researchers to translate basic science results to application developers with greater speed and intensity. We should increase the availability of "incubators," where scientists can interact with system developers, to expedite the use of new technology and new concepts in designs and new products. Certain federally-funded research and development centers are particularly effective at supporting research while finding applications and transition potential.

Ultimately, Vannevar Bush's thesis that there is a major government role in the support of basic research remains valid. There is little viable substitute for engaging good people with good technical oversight, which requires a strong and vibrant science and technology enterprise both within government and outside, interoperating for the benefit of both finding solutions to existing problems, and to explore knowledge for applications yet to be discovered.

The challenge

The proposals presented here are within our reach, and within our abilities. Some might say they are unaffordable, but we already afford, as a society, the best scientists and the best technologists in the world. These goals are intended to inspire our community to continue their leadership, and to build upon our accomplishments, to develop new opportunities, to include new business, new capabilities, and new benefits for mankind.

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Competing interests

The authors declare that they have no competing interests.

Notes

i. http://www.nsf.gov/statistics/seind12/. See Figure 4.2. GERD/GDP has risen from about 2.5% in the early 90's to around 2.8% currently, although federal contribution is relatively flat at around 0.8%.

ii. New and expanding science parks can be found around the globe. In Russia, Medvedev dreams of a US$6.6B city with a "Skolkovo S&T Park" (Atlantic Magazine, October 11, 2011, http://www.theatlantic.com/magazine/archive/2011/10/the-next-russian-revolution/8630/). Incubators in the Middle East and North Africa arise (http://www.infodev.org/en/Project.76.html), while China's Tsinghua Science Park (http://chronicle.com/article/Chinese-Research-Park/124420/) is one among many (http://www.cistc.gov.cn/englishversion/China_ST/China_STAdd2.asp?column=162).

iii. The remaining quarter is largely equivalent to 6.2 Applied Research funding.

iv. The 2012 DSB Task force reports that overall, 9% of personnel of the service laboratories have PhDs.

v. For example, the Department of Energy operates 16 laboratories nationwide, the last of which was founded in 1999, and all others were founded before 1984.

vi. The ten are: Institute for Defense Analyses Studies and Analyses Federally Funded Research and Development Center (Institute for Defense Analyses), National Defense Research Institute (RAND Corp.), C3I Federally Funded Research & Development Center (MITRE Corp.), Institute for Defense Analyses Communications and Computing Federally Funded Research and Development Center (Institute for Defense Analyses), Center for Naval Analyses (The CNA Corporation), Lincoln Laboratory (Massachusetts Institute of Technology), Aerospace Federally Funded Research and Development Center (The Aerospace Corporation), Project Air Force (RAND Corp.), Software Engineering Institute (Carnegie Mellon University), and the Arroyo Center (RAND Corp.).

vii. http://www.nsf.gov/statistics/nsf10305/pdf/tab13.pdf.

viii. We integrate sources that include the Battelle forecast on R&D funding, papers from the World Technology Evaluation Center (www.wtec.org), GAO assessments, the NSF Science and Engineering Indicators, and other academic papers referenced.

ix. President Obama used the phrase in the 2011 State of the Union Speech.

x. There are some suggestions that the Chinese DF-21D, an anti-ship ballistic missile with purported terminal homing capabilities, could present just such an influence in naval operations. The system is discussed in this report: http://project2049.net/documents/chinese_anti_ship_ballistic_missile_asbm.pdf.

xi. Hearing to receive the testimony on the health and status of the defense industrial base and its science and technology–related elements. Testifying: The Honorable Frank Kendall, the Honorable Zachary Lemnios, Mr. Brett Lambert, Mr. Norman Augustine, Dr. Jacques Gansler, and Mr. Philip Odeen.

xii. Bill Gates, quoted in Tom Friedman and Michael Mandelbaum, That Used to be Us, Farrar, Strauss and Giroux, June 2011.

xiii. "Now it is time to take longer strides—time for a great new American enterprise—time for this nation to take a clearly leading role in space achievement, which in many ways may hold the key to our future on earth."

xiv. As a technicality, this permits continued imports, particularly of natural gas, from Canada and Mexico.

xv. Technologies that can accomplish natural interfaces include natural language understanding, eye trackers, personalized assistants that learn, and computer vision systems.

xvi. From the Joint Operating Environment (JOE), 2010, p. 32: "Technology could mitigate the effects of water pollution. By the year 2030, advances in technology may provide many nations with more efficient, sustainable, and affordable means of purifying and desalinating water, providing billions of people with access to clean water and improved sanitation. The ability of the United States and its partners to purify scarce water resources could serve to reduce the potential for interstate friction or state collapse directly related to water scarcity. The development of a rapidly deployable, lightweight and easily maintainable purification system that requires little infrastructure and only modest power generation could likewise increase the effectiveness of humanitarian relief operations."

xvii. See also Executive Order 13031 — Federal Alternative-Fueled Vehicle Leadership 1997.

xviii. "...teams of students in a thousand schools will be able to use advanced 3-D printers to manufacture unmanned vehicles and mobile robots for competitions." October 18, 2010, Remarks by the President at White House Science Fair.

xix. For example, the company HughesNet currently offers direct satellite Internet access at speeds up to 2 Mbps, at prices starting around $60 per month. See http://consumer.hughesnet.com/.

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