J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

PUBLIC POLICY α TOWARDS SCIENCE AND TECHNOLOGY

The long history of American public policy toward science and technology (*S&T*) extends to the beginning of the republic. The impact of these policies upon scientific advance and technological change, however, can only be understood in relation to the international context. At the founding of the republic, science was just developing its footholds in many disciplines. European colleges and institutions such as the Royal Institution of London had been incubating new knowledge resources that were the foundation for the modern sciences including calculus (Newton and Leibniz, 1680s), astronomical physics (Copernicus, Kepler, Galileo, and Newton, 1543–1687), electrochemical physics (Galvani, Volta, Davy, and Faraday, 1791–1820), electromagnetism (Oersted, Ampère, and Faraday, 1820–1830), cellular biology and genetics (Pasteur, Mendel, 1855–1863), chemistry (Priestley, Lavoisier), and the later branch of organic chemistry. With America's origins in agrarian colonialism, much of the early decades of the nineteenth century saw American policies in support of craft technologies, leaving the advancement of science to continue in Europe.

American Science and Technology Institutions in the Nineteenth Century

American public investment in S&T in the beginning of the nineteenth century was largely confined to military and agricultural applications. West Point, as an institution of technical education, had an enormous impact on the American technological environment, informing technological development and engineering for both internal improvements and national security. More directly, the military's investment in organizations such as the Springfield Arsenal, began the long tradition in the American military of closely sponsoring the development of defense-critical technologies. In sponsoring machine tool development for mass manufacturing small arms, the arsenals became a source of technological spin-offs that came to shape innovation in textile machinery, clocks, sewing machines, bicycles, and automobiles (1). Early investment in developing and diffusing agricultural technique was largely undertaken by the states, later to serve as the inspiration for the land-grant colleges of the Morrill Act of 1862 and the agricultural experimentation laboratories of the 1887 Hatch Act. Such investments were critical in transforming America from a backwater frontier-land into an urbanizing, manufacturing center underpinned by a specialized national agricultural enterprise.

However, while American policy focused largely on craft technologies, many Americans traveled to Europe to study in the emerging sciences of chemistry and physics, at universities such as Göttingen and Berlin. As they returned to the United States, they helped agitate for the reform of college curricula to include the sciences and laboratory research (2). Beyond transforming American colleges, this emerging interest group was also increasingly successful at building S&T institutions. The Smithson (1829) bequest that eventually supported the Smithsonian Institution (1846) was the object of such agitation, as some sought to establish a national university, which would have been the first real research institution in America. But, this agitation was successful in getting the National Academy of Sciences founded in 1863 to provide scientific advice to government. Indeed, by the 1880s, there was Congressional consideration of the creation of a U.S. Department of Science (3).

Science became more established in America with the establishment of Yale's Sheffield Scientific School and the Lawrence Scientific School at Harvard in the 1850s. These institutional innovations spurred American colleges to integrate the sciences into their formal organization. But one of the most important S&T-related public policies of the period came with the Morrill Act of 1862, which enabled the establishment of the land-grant universities. After the German research university model was adapted to America with the establishment of Johns Hopkins (1876), the University of Chicago (1892), and Stanford (1891), the land-grant universities were forced to increase their link to scientific and engineering research, just as private institutions such as Columbia and Harvard were.

Rise of Government Involvement in American Science

The US government had relied on scientists in isolated instances prior to 1900. The Navy Depot of Charts and Measures (authorized in 1830 for work on weights and measures), the Army Medical Library (1868), the Army Signal Corps (beginning meteorological work in 1870), and the US Geologic Survey (1879) are such scattered examples. The United State's reliance upon scientists remained limited for two reasons. First, the federal government had not yet become committed to supporting basic science. Second, the range of industries to which science had been applied was limited. Agriculture and natural resource-related industries had only begun to draw upon scientific knowledge. There was no real health industry. The only other science-based industries in the American experience were electrification, telephony, and electrochemical industries. The National Bureau of Standards (*NBS*) was developed in 1901 to deal with technical standards related to each of these industries, as well as craft-based industries. From then, the NBS began a long tradition of conducting both path-breaking and infrastructural scientific and technical work which soon included radio, aircraft, metallurgical work, and a range of chemical work. Both World Wars found NBS deeply involved in mobilizing science to solve pressing weapons and war materials problems. After World War II, basic programs in nuclear and atomic physics, electronics, mathematics, computer research, and polymers, as well as instrumentation, standards, and measurement research, were instituted.

Until World War II, the federal government's involvement in science and technology remained limited to the above, save for one important instance. In 1915, the National Advisory Committee on Aeronautics (*NACA*) was established to help build the emerging American aircraft industry by coordinating S&T efforts by government agencies and firms. The proximate cause for its establishment was the war. But a community of scientists and technicians had been pushing for the establishment of a federal aviation lab since 1911 (4). Though conducting little R&D prior to the end of World War I, this organization was very effective in supporting the development of civilian and military aircraft throughout the 1920s to the 1940s. The NACA conducted much of the research into airfoils and aerodynamics, including associated instrumentation, while the military services concentrated on engine development in cooperation with engine manufacturers. This partnership, under federal procurement policy, let America regain by 1925 the lead it lost in 1910, becoming the lead innovator in large civilian transports and, consequently, long-range bombers. This organization, however, was not responsible for early innovations in supersonic flight and jet propulsion that Germany pioneered.

By the early 1930's, America had developed a rather strong technological enterprise through the intersection of industrial development and the development of engineering and applied sciences at American universities. America was still lagging as a leader in fundamental science. Germany was the definitive leader across a range of disciplines. But, with the rise of the Nazi regime in Germany, many German Jewish scientists sought refuge in Allied countries. America's physics and chemistry enterprises were transformed in the process. Indeed, it was these émigrés who informed the American military of the potential of science-based weapons such as the atomic bomb. Universities such as Columbia, Harvard, Chicago, and Berkeley became academic powerhouses and also became the foundation upon which much of the wartime science and technology effort was built.

The emigration of European scientists did more for the American scientific enterprise during the 1930s than did government policy. Herbert Hoover, while a staunch supporter of anything scientific or technical, was committed to “associationalist” political principles, favoring voluntarist activity over government action (5). As a result, Hoover did much to encourage corporate and philanthropic investment in basic science, understanding that America lagged in this mode of scientific inquiry. He encouraged the development of a private basic science fund, but government support, in his view, should remain minimal. Interestingly, Hoover was a strong supporter of government support of R&D and infrastructure related to the aircraft industry, perhaps explained by the industry’s linking of the civilian industry’s success to national security goals.

With the onslaught of World War II, the American military began to organize national science and technology resources to support the war effort. The wartime Office of Scientific Research and Development (*OSRD*) was formed as a civilian organization, headed by the MIT electrical engineer Vannevar Bush, who left the Presidency of the Carnegie Institution of Washington to fill this new role (6). The OSRD was the vehicle by which the nation’s scientists were harnessed to define and meet a range of technological goals including the atomic bomb, proximity fuse, radar, and sonar (7). The OSRD organized scientists into teams closely focused on particular scientific or technological problems that were part of a larger technological problem. The policies governing wartime S&T were highly mission-oriented, with peer review playing a limited role within this larger context.

Vannevar Bush and the Linear Model

After the wild success of American S&T in providing wartime technological superiority, Bush responded to President Roosevelt request for a report outlining a peacetime arrangement for the public support of science. After Roosevelt’s death, Bush presented President Truman with *Science—The Endless Frontier* (8), which served as the chief articulation of the “social contract” that governed the relationship between science and the federal government until the end of the Cold War. In return for all the resources that the scientific community needed, the report promised that science would provide for national security, national health, and national prosperity.

Several features of this report are critical in understanding the development of the scientific community during the Cold War. Bush was crafting a plan for the support of basic science in a way that demilitarized science. In doing so, Bush advocated, if implicity, a few key design principles for America’s peacetime science policy: (1) science should be politically autonomous and have its own self-regulating governance structures; (2) science should be designed around the academic model of individual achievement; and (3) science is assumed to drive technological innovation through a linear model (see Fig. 1) with basic scientific advances fueling applied research, then development work, and ultimately product commercialization. While not explicit in the report, the linear model is widely understood to have originated with this particular policy pronouncement (9,10).

Bush’s plan called for a single national funding agency for science, the National Research Foundation, to be under the control of the scientific community. However, the post-WWII political perturbations in Congress brought this particular vision under scrutiny. The famous Bush-Kilgore debates, involving West Virginia Senator Harley Kilgore, engulfed the NRF plans, preventing the establishment of such an organization until 1950, as the notion of the political autonomy of science was seriously challenged. Meanwhile, the S&T assets built-up during World War II were brought under the wing of the newly established Atomic Energy Commission (*AEC*) and the Office of Naval Research (*ONR*), ensuring that post-WWII American science enterprise would experience a heavy military influence. The one exception was the National Institutes of Health, which had by then already taken on an institutional and political life of its own. When the National Science Foundation was established in 1950, it was only to have a relatively minor role in shaping the American science enterprise.

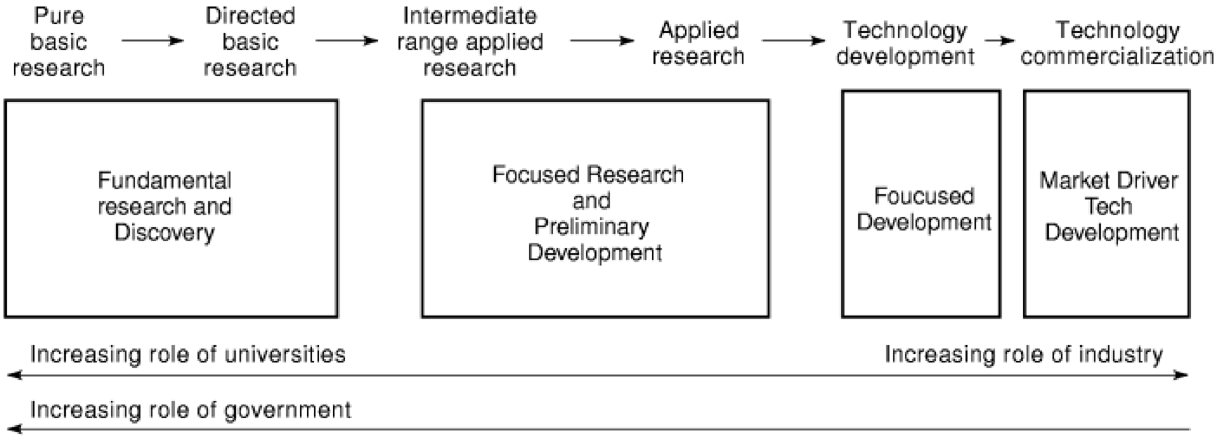

Fig. 1. Linear model of technological development.

Deviating from the Linear Model: The Militarization of American Science and Technology

The linear model of technological development was implicit in the Bush report. This general view was shaped by the political commitments of Bush. First, his intention in writing the report was to encourage the federal government to become a permanent patron of basic science. Second, he wanted to demilitarize the American science enterprise, placing all basic research funding under the control of one civilian foundation. Third, he believed in a minimal role for the government in the economy, seeking to encourage industrial innovation through the patent system, scientific and technical manpower, and the funding of basic science. In his view, the private sector would conduct all R&D, beyond basic research, at optimal levels. These political views were considerably more conservative than those of Senator Kilgore, who sought a science and technology enterprise engaged more directly in treating issues such as socioeconomic equality.

This conception of technological development was championed by the academic science community and the private sector, as it, in effect, argued for the autonomy of academic science and the protection of business from government intrusion into the technological aspects of their industries. However, as Bush's policy proposal stalled in Congress, the militarization of the American science base led to a reality quite different from that encouraged by the linear model. With the militarization of the aviation/avionics, nuclear power, and electronics/computers industries, much of the cutting-edge technological innovation within the American national innovation system was induced by government policy. As a result, the standard linear model dynamics were matched by the opposite dynamic of massive, complex technological systems fueling basic scientific inquiry in many disciplines, thereby rendering the assumptions of the linear model problematic for policymaking.

The national laboratories that were organized out of the Manhattan Project's laboratories grew as the nation's commitment to nuclear weapons strengthened. The militarization of the nation's S&T enterprise grew impressively with the Soviet launch of the satellite *Sputnik* in 1957. At this point, the NACA was transformed into the National Aeronautics and Space Administration (*NASA*), and a new entity named the Advanced Research Projects Agency (*ARPA*) was developed within the Department of Defense to help America recapture the technological edge in the Cold War. The first was originally chartered to ensure that America was capable of competing in space, and was soon refocused by President Kennedy to put a man on the moon. NASA partnered with many of the same defense contractors involved in developing nuclear launching capability. The second, ARPA, was chartered as a unit of the Office of the Secretary of Defense, to help better coordinate advanced research with the military services. ARPA would partner with the services to pioneer new, defense-critical technological systems.

Funding levels for science and technology leapt dramatically as a result of these two organizations, particularly NASA. The mobilization of scientific and technical personnel in the private sector and military was very large, and graduate science and engineering education changed in scale and scope.

In contrast with the linear model of the Bush conception, the militarization of the American science enterprise brought much of the American basic science enterprise under the command of the military's technological imperatives. Fundamental scientific inquiry was supported in areas critical to the ongoing development of major weapons systems. Given the range of weapons systems, however, this meant the large-scale support of virtually every area of science. Four categories of research (naval, aviation/aerospace, electronics/computers, and nuclear) alone required sustained funding of every field of science outside the health, biological, and agricultural sciences.

Health and Agricultural Research: A Digression

These three domains of research were sustained by very different policy regimes. In America, biological and health research had its roots in the military's concern over troop losses due to disease and illness. Indeed, in the Civil War and the Spanish American War, more troops had been lost to disease than any other cause. This began an ongoing military commitment to health research, clinical technique development, public health efforts, and medical library development. Soon, this spurred the development of public health agencies at the state level, as well as progressive public health movements. The National Institutes of Health (*NIH*), founded in 1930, was a result of this larger concern for health, which both relied upon and encouraged a growing fundamental knowledge base about the biological basis for disease and illness.

While health research began as a national security priority, it soon evolved into a public health priority with the political dynamics changing accordingly. It became a professionalized, bureaucratic political force tied to progressive ideals. However, as the NIH became involved, the model changed significantly with the dramatic growth in health research driven by disease-centered constituency groups (10a,10b). The proliferation of disease-oriented institutes within the NIH became the vehicle for the advance of health research, focused more narrowly on biomedical research and development.

Agricultural research, as mentioned above, became established in America through state governments. Some states, such as New York, had developed farmers institutes in the 1830s and 1840s to encourage progressive farming techniques. Meanwhile, in Germany, their advanced knowledge of chemistry became applied to agriculture through agricultural experiment laboratories (11). Some advocated the development of institutions dedicated to applying chemical knowledge to agriculture, but this was to have little direct impact on American agriculture for some time.

Little federal action was taken to support agriculture through research until the Morrill Act. After this law developed the land-grant college system, which was then passed off to the states to manage, the Hatch Act called for the development of agricultural experiment laboratories attached to the agricultural colleges. The original commitment of such institutions was to generate new knowledge and disseminate existing technical knowledge for the improvement of agricultural practice. But this dissemination function was uncoordinated and fraught with difficulties until the development of the extension stations after 1914 under the Smith-Lever Act. However, the policy commitment to agricultural R&D began a path of scientific and technical knowledge development that was later to profoundly affect the performance of American agriculture.

These stations brought chemical and biological research to the field to help increase productivity. As they were related to the land-grant colleges, they were part of a disciplinary growth and specialization process that brought scientists and engineers into every aspect of agricultural production and processing as it relates to nearly every crop or domesticated animal in America. The tension between the land-grant disciplines and the extension stations inspired new knowledge development, and linked the more applied bodies of knowledge to fundamental developments in chemistry and biology. By 1940 gains in agricultural productivity were heavily reliant upon science. This trend has only continued.

This agricultural research system was propelled by a network of constituents. The land-grant/extension institution was considered a success insofar as it catered to and supported the agricultural and mechanical industries within each state. Highly democratic in form, investments in scientific research, technological development, and institution building were determined through a complex process of continuously interacting farm and industry interests, scientific and technical personnel, and elected officials.

Instability in the Science Policy System: The 1970s

A number of factors emerged in the late 1960s and early 1970s that fueled instabilities in the American research system. Anti-Vietnam War sentiments on the campuses of American research universities and, more specifically, student and faculty opposition to performing military R&D on university campuses, led to a shift of military research off of many campuses. Certain campuses, such as MIT and Johns Hopkins, remained major recipients of military R&D monies. But such an opposition led to increasing tensions between the largest patrons of academic research and academic institutions.

Much of the 1970s was characterized by the "Energy Crisis" and the ensuing economic pattern of "stagflation." Pressure to reduce the cost of petroleum and, more generally, energy, caused the rapid growth and reorganization of various energy research organizations, under the Energy Research and Development Administration in 1975. Soon after, President Carter reorganized these former AEC R&D assets under a new Department of Energy (1977). Beyond the programs built to respond to the energy crisis, this included the weapons laboratories (Sandia, Los Alamos, Lawrence Livermore) and the multiprogram laboratories (Brookhaven, Oak Ridge, Lawrence Berkeley, Argonne) commonly referred to as "national laboratories." Linked to the R&D response to the energy crisis was consideration of the environmental aspects of nuclear energy and fossil fuels. Major R&D programs were launched to develop environmentally friendly energy sources, including solar energy. These programs were largely gutted when the Reagan Administration entered office in 1981.

The economic instability associated with the energy crisis was matched by the globalization of manufacturing, with Japan, Korea, Taiwan, and other newly industrializing countries (*NIC*) increasingly penetrating the American domestic market. This brought some American policy makers to begin considering the competitiveness aspects of R&D policies. Civilian technology-development programs that had been advanced by the Kennedy Administration were being reconsidered as vehicles for enhancing American industry's technological capabilities

Finally, the 1970s featured the redefinition of the Soviet threat by the American intelligence and military communities. This new assessment found that the Soviet nuclear ballistic missile threat was considerably more menacing than commonly thought.

Competitiveness and National Security: The Reagan Years for R&D

The Reagan Administration drew upon the redefined Soviet threat to fuel a very large build-up of US strategic capability, including intercontinental ballistic missiles (*ICBM*), nuclear submarines, cruise missiles, and the controversial "Star Wars" anti-ballistic defense umbrella. This entailed a massive military R&D mobilization, mostly concentrated on the development side of the equation. Though some of these technologies were supported during the Carter Administration, this generation of technological applications was the most publicized of the Reagan military build-up, but the military R&D portfolio included generations of weapons that would not be observed until the Persian Gulf War in 1991, such as stealth aircraft, "smart bombs," and intelligent command, control, communications, and computer systems. While dedication of funds to these S&T endeavors ballooned

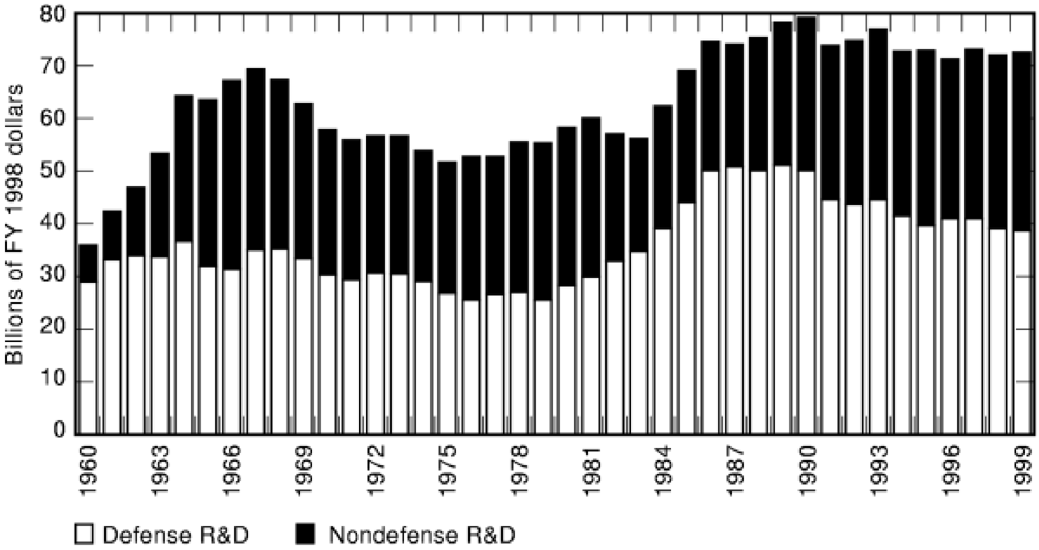

Fig. 2. Federal spending on defense and nondefense R&D. (Source: OMB Historical Tables).

the military portion of the American R&D budget, the nondefense science budget remained rather flat (see Fig. 2). But other policy mechanisms were created to foster civilian technology development. Two landmark pieces of legislation—the University and Small Business Patent Procedures Act of 1980 (Bayh-Dole Act) and the Technology Innovation Act of 1980 (Stevenson-Wydler Act)—sought to foster the competitiveness of American firms.

The Bayh-Dole Act was created to encourage institutions performing federally funded scientific and engineering research to patent the fruits of such research. This law created incentives for universities and other nonprofit research institutions to develop technology transfer offices to identify, protect, and transfer inventions made by their researchers. The rationale behind this legislation was to get the results of federally funded research into the public domain; a rationale encouraged by those thinking that technological inventions were not making their way into the marketplace (12). This legislation built upon technology-transfer legislation targeted at the military R&D establishment during the 1970s, conceived to provide the legal mechanisms necessary for the transfer of the rights relating to particular technologies between military R&D organizations and defense contractors.

The Stevenson-Wydler Act articulated a broader role for government in promoting commercial innovation and established the first major initiative to proactively transfer technology from federal labs to industry. This act made technology transfer an explicit mission of the federal labs, establishing an office within each lab charged with identifying technologies with commercial potential and transferring that knowledge to US industry.

Meanwhile, the notion of a coordinated industrial policy boiled up within the Democratic Party, first in 1980, with the advocacy of Sen. Adlai Stevenson (D-IL) and some in the Carter Administration's Department of Commerce. Democrats within the House continued thinking about a coordinated industrial policy, most clearly within Congressman LaFalce's Economic Stabilization Subcommittee of the House Banking Committee. By the end of 1983, this committee had developed a plan that was very similar to those proposed by unions such as the UAW and AFL-CIO. This plan was largely oriented around coordinating financial resources allocation and regulation across a range of major industries, intended to help coordinate growth or decline more responsibly than the market. But there was some attention paid to civilian R&D to revitalize mature industries and to support emerging industries (13).

After industrial policy was defeated with Mondale's loss to Reagan in 1984, policies connected to civilian-related science and technology became more closely related to the competitiveness concerns that would later be shared by Congressional Democrats and President Bush. The concern for government-sponsored R&D, as it related to civilian technology, was seen later in the 1988 Omnibus Trade and Competitiveness Act, which created the Advanced Technology Program (*ATP*) and the Manufacturing Extension Program (*MEP*) within the National Bureau of Standards (*NBS*). This, and the related NIST Authorization Act of 1989, created the Department of Commerce's Technology Administration and renamed the NBS as the National Institutes for Standards and Technology (*NIST*). These legislative efforts sought to augment the Institute's customer-driven, laboratory-based research program aimed at enhancing the competitiveness of American industry by creating new program elements designed to help industry speed the commercialization of new technology.

Much in line with the Reagan Administration's attitude toward government involvement in civilian technology, the Federal Technology Transfer Act (*FTTA*) was passed in 1986 to leverage existing investments in mission-related R&D for the support of industrial technology development. This was done rather than developing programs designed specifically for such a task. The FTTA authorized federal agencies to enter into cooperative research and development agreements (*CRADA*) with companies, universities, and nonprofit institutions, for the purpose of conducting research of benefit to both the Federal government and the CRADA partner. The impacts of the FTTA-instigated CRADAs on the integrity of these laboratory assets has largely been ignored, despite significant evidence that they influence the character of the labs. But, since its inception in 1986, the CRADA mechanism has been strongly embraced by industry.

An interesting departure from the post-WWII S&T policy consensus came in a 1983 report to the White House Science Council from the Federal Laboratory Review Panel, chaired by industrial research mogul David Packard. While the rest of the S&T community had largely been satisfied with science as it was organized in relation to the military missions (science is good, labs are good), this report made a serious departure from the basic notions underpinning this consensus. The report was a scathing attack on the federal research laboratory establishment, calling for major institutional changes to encourage better laboratory performance in terms of supporting scientific advance and technological change. Attention was turning to how elements of the American research system were designed. That major portions of the federal S&T establishment (in this case, the national laboratories) were poorly organized was never before a prominent theme in the science policy discussions, even though such concerns did not escape those concerned with the operation of such assets.

There were other moves in the American research system to promote commercial technology during this period, but they were aimed at doing as little as possible to have public support for R&D programs explicitly designed for that goal. For instance, such moves were seen within the National Science Foundation. But it was not until the Bush Administration that programs such as ATP and MEP were built to specifically deal with questions of civilian technology development.

Universities and Federal Science and Technology Policy

In 1945, when Vannevar Bush wrote *Science—The Endless Frontier,* he was sanguine about the promise of science. Yet he was quick to note that there was only a handful of research-intensive universities of the highest caliber. While he did not name them specifically, it is commonly believed that he was referring to Columbia, Harvard, Stanford, Chicago, and Johns Hopkins (14). He was interested in seeing a larger number of universities at the frontiers of knowledge creation, though his elite conception of science idealized the continuation of a small and distinguished community of scientists. Insofar as Bush's report adhered to a linear conception of technological development, the academic science enterprise would play a critical role in driving fundamental discovery and, consequently, technological innovation.

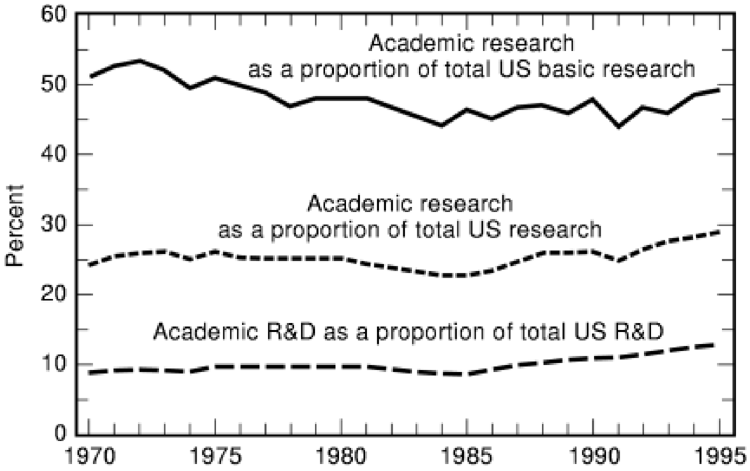

Fig. 3. Academic R&D, research, and basic research as a proportion of US totals. Academic research includes basic research and applied research. Data for 1994 and 1995 are estimates. (Source: NS Science & Engineering Indicators, 1996.)

Two of Vannevar Bush's themes worked to the advantage of research universities. First, his focus on unfettered basic research favored an academic setting. His vision of demilitarized science was not to be, but the military did much to support fundamental scientific inquiry within a university setting, understanding that some degree of scientific autonomy was essential to the enterprise. Second, his focus on scientific and technical personnel as one of the most important commodities favored a university setting, since the cutting-edge research was routinely combined with graduate education and training. This meant that there would be a continuous stream of new scientists and engineers familiar with the state of the art and the topography of the research frontiers (see Fig. 3).

Vannevar Bush's original call for $10 million a year for academic research, in retrospect, was implausible. Instead, federal R&D funding in and beyond the universities was significantly larger. Not only was the scale of R&D funding much larger, but the range of academic research institutions that developed with this funding was staggering (see Fig. 4). The dispersion of federal funding for academic research affected a rising tide that raised all ships. By and large, the leading research universities of 1945 maintained much of their leadership. But, as scientific and engineering knowledge specialized and proliferated new bodies of knowledge, there was more room for institutional leadership. Various universities became premiere research institutions in specialized areas. Different universities developed their own institutional strategies, and consequently, their own distinct research portfolios. From this specialization, and the contingencies of emergent fields of research, the top ranks of American research universities came to include universities that had virtually no standing as research institutions in 1945 (15).

Because of the standard raised by those like Vannevar Bush, the institution of the "American research university" served as a guiding force for up-start institutions. These universities developed research portfolios by developing research programs competing for funding from competitive funding sources such as NSF peer review. However, their building strategies required significant institutional entrepreneurialism, and the acquisition of resources over and beyond the monies provided by research grants. Given this situation, state universities made significant leaps in status because of their ability to summon state legislatures to make investments in the state university system. Private universities, constrained by their gifts and endowments, had less support from state sources, leaving them to develop their research infrastructure with their own internal resources and an internal tax on research grants, a mechanism typically called indirect cost recovery (*ICR*). ICR was allowed by the federal government, at a certain percentage of the awarded funds, to cover

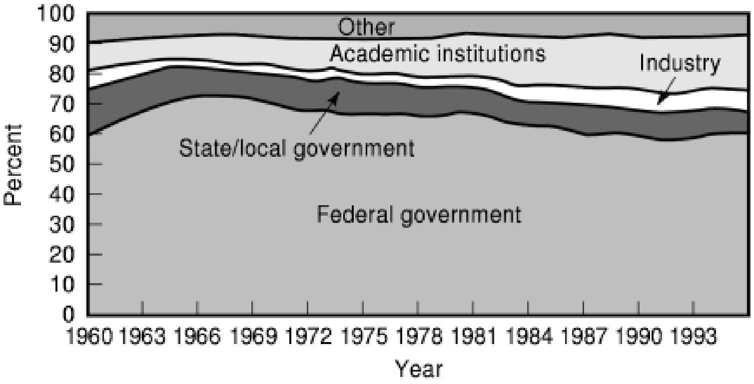

Fig. 4. Sources of academic R&D funding, by sector.

expenses related to the support of sponsored projects but which cannot be identified readily with a particular project. Allowable indirect costs fell into the general categories of use (depreciation) allowance for buildings and equipment, institutional operation and maintenance expenses, library expenses, and expenses related to grants and contract administration by university, college, and departmental offices. State universities also engaged in ICR, but were able to maintain significantly lower ICR rates because of state funds. As these other universities gained prominence as research leaders, this placed significant pressures on the universities previously allowed to charge higher ICR rates to bring their ICR rates down. The White House Office of Management and Budget (*OMB*) began a process in the early 1990s of revising its A-21 Circular, which eventually led to the downward revision of allowable ICR rates for this set of universities, beginning a process of cost-shifting. This cost-shifting was a manifestation of changing federal attitudes toward university research, seeing universities less as performers of federally funded research, and more as expenditures, requiring fiscal discipline.

Within this policy context, universities served as incubators for innovative S&T personnel, new science-based firms, and the bodies of knowledge that underpinned entire industries. The American microelectronics and computer industries were intimately linked with Stanford, MIT, Carnegie-Mellon, and Harvard. The pharmaceuticals industry thrived off academic research and trained researchers, and was enabled by the rise of academic medical centers for clinical trials. The biotechnology industry similarly thrived because of the NIH/academic medical center complex, supplemented by complementary federal investments in university-based agricultural research. MIT was heavily involved with the development of numerically controlled machine tools, reshaping the dynamics of manufacturing. In earlier eras, both wired and wireless communications were tied intimately to Columbia, Stanford, and MIT.

In broader terms, the professionalization of the engineering and applied sciences disciplines that both paced and enabled the development of a range of industries was fundamentally tied to universities. Aeronautical engineering, electrical engineering, chemical engineering, computer science, and automotive engineering are some of the more prominent examples of the way in which these university-centered technological communities developed to support various industries and their associated technologies.

Corporate R&D and Federal Science and Technology Policy

Corporate R&D was a rather rare activity prior to the turn of century. During the 1830s and 1840s, some chemists, largely trained in Germany, did contract research for companies on various issues related to their materials and processes. Industrial research remained focused on the testing and grading of materials for the steel, textiles, and chemicals industries for much of the nineteenth century. The exceptions to this rule had their birth in the telephony and electric lighting industries. Fundamentally reliant upon the scientific insights of researchers based largely in European universities, electric lighting innovators were forced to apply their scientific knowledge to develop viable lighting, generation, and distribution technologies. Many of the early American entrepreneurs in this industry were university-trained. Their budding firms were organized around their laboratories. The first industrial R&D lab of significance is typically attributed to Thomas Edison. But his competitors in the late 1870s and early 1880s quickly emulated his organization. By the end of the nineteenth century, Edison's General Electric and Westinghouse were major performers of R&D, engaging a full range of basic and applied scientific and engineering questions. Western Electric, later the production arm of AT&T, also developed labs which were reorganized in 1907 and established as Bell Laboratories in 1925. Electrochemical firms such as Union Carbide, Dow, 3M, and ALCOA were setting up research laboratories during the late 1890s and early 1900s, at the center of a research-intensive industry. Du Pont founded its corporate central laboratories at the turn of the century.

Despite all this, organized R&D was not being applied to most of American industry. This, however, was to change in the wake of World War I. As Germany transformed into an aggressor, the United States was caught in an awkward situation, industrially. Germany, as the world leader in bulk- and fine-chemicals, provided US industry with many key chemicals. As Germany cut off the United States and the allies from these products, solutions had to be developed in order to meet basic production needs. Coordinating industrial R&D capability with government and university scientific knowledge, the nation successfully overcame these knowledge barriers. American industry perceived this victory as the result of organized R&D and extrapolated a utility for R&D in industrial competition more broadly. As a result, industrial investment in organized R&D expanded greatly during the 1920s. It came to affect a wide range of industries that are not considered science-based. Organized R&D was used to refine material inputs into such industries as automobiles. It was also at the core of industries such as telephony, radio, electronics, specialty metals, and chemical industries. This dynamic was, in part, related to the increasing development of related fields of knowledge; a process based in the scientific information networks centered on research universities. But corporate decision makers were explicit about the role of World War I in shaping their technology strategies.

However, while a wide population of corporations began to support organized R&D during this period, there was also significant federal support of several key industries. Agricultural R&D had been a mainstay of federal patronage, as witnesses in the Morrill, Hatch, and Smith-Lever acts, and this pattern continued during this period. The aircraft industry was not only supported by but also implicated in the federal technology development activities centered around the NACA and the military services. Radio, in the American context, saw major R&D support from the National Bureau of Standards and the military services. Major industries saw substantial federal R&D support, despite the American government's less than enthusiastic support of science and technology more generally.

Corporate R&D changed dramatically after World War II. In agriculture, the state of the sciences had changed under decades of federal patronage such that major private investment in R&D related to both production and processing were enabled. Because of the Cold War, industries involved with the development of defense-critical technologies, such as nuclear devices, the nuclear navy, supersonic aircraft, and long-range aircraft, saw federal support through federally funded research and development centers (*FFRDC*). The scale and scope of the American Cold War defense strategy forced the government to enlist companies across a spectrum of technologies in defense technology development. This meant the development of specialized corporate R&D competencies that had significant impacts on the national economy (16).

One distinct feature of much of the twentieth century has been the "corporate central research laboratory." The largest of the nation's science-driven firms spent most of the century organized around such laboratories that not only served the companies' product development, system-maintenance, or competitor analysis needs, but also supported a significant amount of fundamental research. The often-cited example is AT&T's Bell Laboratories, which was the birthing ground of the transistor. But as competitive pressures mounted within many of these industries, firms began shedding their corporate central research laboratories in favor of other R&D arrangements, often at the expense of longer-term research. Given the very important role that the longer-term research conducted by these corporate labs played in the national innovation system, the collapse of corporate central research has been considered a critical policy question (17,18).

Expert Advice and Politics: Change Over Time

While much of the prior discussion has dealt with public policy in support of science and technology, the following will also focus on science and engineering informing policy making. Scientific and technological advice to government has changed over time as institutional capacities have evolved. In 1848, the American Association for the Advancement of Science (*AAAS*) was formed to bring the nation's scientists together, and this organization had, as one of its primary goals, the establishment of a central government scientific organization. The organization's advice on this subject went largely unheeded. Rather than building a central organization, Congress established the National Academy of Sciences (*NAS*) in 1863, in response to the Civil War, to provide science advice to government. But this advice was largely heeded only when convenient, with the Academy having little power over decisions such as the appointment of bureau chiefs. However, this network of scientists continuously promoted scientist involvement in government, as well as particular scientific and technical activities in support of the government's missions. As a result, various public agencies were developed to undertake R&D. With the development of new public R&D capacities, scientific advice began to inform policy making. Scientists also became influential in state level policy making as the land-grant universities developed a range of specialties.

With the onslaught of the first World War, scientific advice again was drawn upon to achieve public goals. The National Research Council (*NRC*) was established in 1916 to coordinate research for the war effort. Earlier, government's role in the cases of aircraft, radio, and chemicals was discussed. In this case of science advice, there was a healthy interplay between science advising policy making, and public policy goals shaping science. Within the post-WWII Bush paradigm, however, this interplay broke down, at least rhetorically. As the American science community fought for autonomy under the Bush plan, it argued that science should be left to its own devices.

Two other instances of scientific and technical advice cannot be ignored. First, beginning under President Truman, formal structures for science advice to the President were devised. The Office of Science and Technology Policy (*OSTP*) was soon institutionalized within the Executive Office of the President, for several purposes. OSTP was to enable the President to mobilize science in case of war. Also, it was to bring some coordination to science and engineering research programs at the Presidential level. The director of OSTP, and Science Advisor to the President, would preside over a council of scientists brought in from academe and industry. Many incarnations of this general structure have come and gone over the years. Second, the Office of Technology Assessment was developed as a Congressional agency in the mid-1970s, to help the government make more informed decisions relating to its R&D funding and policy decisions. While bipartisanly applauded for its quality assessments, it was eliminated in 1995 by the incoming Republican majority.

Such autonomy would never materialize, as the Cold War once again placed the military over much of the American science enterprise, this despite the foundation of the NSF and the NIH. Scientists and engineers served on any number of advisory boards at all levels of military decision making such as the very important Defense Science Board. Outside of the military R&D establishment, scientists and engineers served as advisors for more and more government activities as they became more technical in nature. Indeed, this highly decentralized set of roles for scientists within the American government has had a profound impact on a range of government functions.

While autonomy has not materialized in the way Vannevar Bush would have liked, the rhetoric of scientific autonomy has prevented the development of institutional mechanisms for linking scientific priority setting to

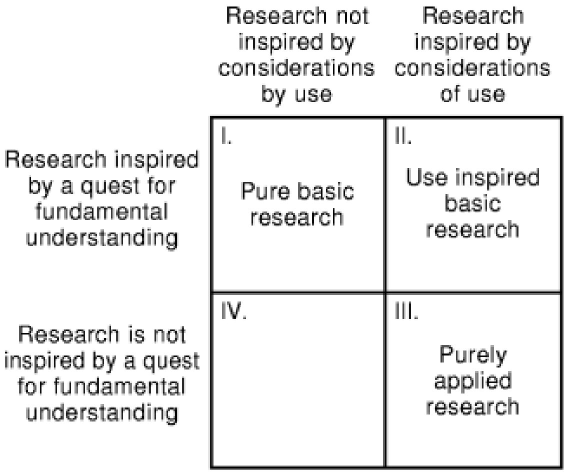

Fig. 5. Pasteur's quadrant research.

national goals. At best, ad hoc and transient policies have been developed to attempt such a linkage. Along with the rhetoric of autonomy has come the notion of peer-reviewed science, wherein scientific peers are only legitimate decision makers for which science should be supported. However, this rhetoric has always missed the complexity of the allocation of resources among the sciences. With all scientists' opinions holding equal standing, and each scientists operating from his/her own disciplinary background, the question of which discipline or subdiscipline deserves more funding has been a perennial subject of debate (19).

While the performance of government has benefited greatly from the scientific advice across many different policy domains, the scientific community has continued to grapple with advising on its own governance and the policies that should be applied to it.

Recent Issues in Science and Technology Policy

In recent years there have been several challenges to status quo of the American science and technology policy. First, there has been new thinking about the limitations of the linear model of technological innovation. Second, new patterns of innovation have evolved. And last, there have been new realizations about the relationship of science and technology to national goals.

Major limitations to the linear model, as articulated in *Science—The Endless Frontier,* have recently been specified. Stokes (9) critiqued the linear model in terms of its failure to distinguish the motivation of the researcher. The linear model makes a distinction between basic and applied research, with the first aimed at inquiry into fundamental natural phenomena and the second aimed at applying these insights to the solving of particular problems (see Fig. 5).

Stokes, observing the work of scientists like Louis Pasteur, noted that the linear model ignored fundamental research conducted by a researcher inspired by use considerations. This alone posed a formidable challenge to the linear model.

Another challenge was posed by Branscomb (20), noting that there is not only fundamental scientific research, but also fundamental technology research. His argument compared the barriers associated with fundamental technology research and fundamental scientific research, noting that the private sector will underinvest in them for similar reasons. The linear model made no allowance for the notion of fundamental technology research, though experience with emerging technologies highlights its importance. Branscomb rightly concludes that policy makers should not be concerned with devising a science policy and a companion technology policy, but rather an integrated research policy.

A third challenge to the linear model has been the emergence of interdisciplinary research. The linear model was very much committed to the disciplinary model of academic research. Peers within a discipline would have control over the governance of their realm. While questions of allocation of funds among the sciences went unanswered, this disciplinary model continued to muddle along. However, many scientific questions arose that attracted the interest of a number of different scientific disciplines, each with a legitimate right to lay stakes on the intellectual space occupied by a phenomenon. The study of global climate change is one such phenomenon. Mental illness is another. Evolutionary population dynamics are yet another. While several different disciplines allocated their attention to each, the problem of disciplinary conflicts has arisen. This has raised questions about who should be defining the phenomena to be studied and setting the scientific agendas (21). The principle of scientific autonomy has become much more complex as phenomena that naturally inspire interdisciplinary research place pressure on the research system to adjust its decision-making processes. In the case of global climate change, this has gone so far as to bring in nonscience stakeholders to shape the policy-making process.

New patterns of innovation have also raised a number of issues of late. This is seen in concern over the internationalization of R&D. Also, many have been concerned with the state of industrial research after the collapse of the corporate central research labs in the 1980s and 1990s. Many have become worried about the possibility of academic research losing its traditional openness as commercial stakes increase through university patenting under Bayh-Dole and the rise in the number of university-industry research centers.

The internationalization of R&D has become a point of tension for policy makers. Three main issues have become prominent. First, the inability of a particular country to appropriate the full returns from its investment in R&D has made domestic science and technology making within an international context very complex. Second, with "big science" projects requiring massive capital outlays, yet involving an international community of scholars, the development and maintenance of coherent governing and funding coalitions has been highly problematic. This has been exacerbated by the long-term nature of the commitment. Third, with large corporations serving various regional markets within the global context, many firms have come to develop elaborate R&D networks, with research facilities located all over the world. This has made the training of scientific and technical personnel critical to a nation's ability to attract investment for high-skilled jobs, drastically reworking the international political economy.

The collapse of corporate research, as discussed earlier, continues to be an active policy consideration. In its wake, many are attempting to evaluate the actual impact this change is having on the innovative capacity of firms. When held in tension with the third pattern, the dramatic rise in university-industry research centers, many in the science and technology policy community are attempting to understand the ways in which these two forms of research organization differ in performance.

Related to these recent issues is a set of new realizations in American science and technology policy. Vannevar Bush's linear model called for scientific autonomy, but American science was clearly placed in the service of the military. (This is not to mention the large proportion of federal R&D put into biomedical research). With the end of the Cold War, the thought that science and technology should be better linked to a wider range of national needs has been articulated by several prominent public figures [e.g., Brown (22)]. Science should not be an end in itself, but a tool for the accomplishment of higher-order goals. Part of this realization has been the understanding that there are limits to what science and technology can accomplish on their own. With this, science and technology must be understood as one of many modes of social activity, which holds a special place in relation to each of many other social activities.

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CHRISTOPHER TUCKER
Columbia University