Where Do Innovations Come From? Transformations in the U.S. National Innovation System, 1970-2006[1]

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Today, approximately two-thirds of the award-winning U.S. innovations involve some kind of interorganizational collaboration—a situation that reflects the more collaborative nature of the innovation process and the greater role in private sector innovation by government agencies, federal laboratories, and research universities.

How should the United States craft policies that effectively spur technological innovation? With increasing competitive challenges from other nations, particularly in technology and innovation-based sectors once thought to be largely immune from foreign competition, there is increasing interest in crafting policies to help spur innovation. But if innovation policies are to be effective, it's critical that they be based on an accurate understanding of the U.S. innovation system—in particular, an understanding of where U.S. innovations come from. This report does this by analyzing the sources of award-winning innovations over the past few decades. It finds that the sources of these innovations have changed in two key ways. First, large firms acting on their own account for a much smaller share of award-winning innovations, while innovations stemming from collaborations with spin-offs from universities and federal laboratories make up a much larger share. Second, the number of innovations that are federally-funded has increased dramatically. These findings suggest that the U.S. innovation system has become much more collaborative in nature. Federal innovation policy needs to reflect this fact.

THE INNOVATION POLICY DEBATE

Many scholars, policy analysts, and policymakers interested in innovation policy assume that most innovations come from the private sector acting alone and that government's role in supporting innovation is limited. As a result, many of these individuals limit their recommendations to "innovation environment" measures—for example, ensuring a good business climate and expanding basic science and the supply of scientific and technical talent—that will let the private sector continue to innovate on its own.

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They believe that the vitality of the U.S. economy rests almost exclusively on the dynamism of the private sector. Thus, a too-active government innovation and technology policy, beyond support for basic research and science, technology, engineering, and mathematics education, is "industrial policy"—a short hand pejorative for inappropriate intervention into markets that either hinders private firms from developing innovative technologies, and/or distorts the efficient market-based allocation of resources.

An opposing view held by other scholars, policy analysts, and policymakers is that government funding beyond support for basic research and procurement has played a key role in the technological breakthroughs that have sustained U.S. industry's global predominance since World War II and that the government's role in coordinating collaborations between private industry and publicly funded research in university and government laboratories has spilled far beyond the defense sector to include large parts of the civilian economy.[2] Many of these individuals believe that if networks involving government research and development (R&D) programs and scientific and technical experts have been at the heart of the innovation economy, then policies that limit or even roll back government involvement in innovation are counterproductive. Instead, effective technology policies would require active government support of targeted R&D programs and collaborative mechanisms that support innovation.

These disagreements are typically fought out in the realm of world views. Individuals who believe the private sector does most innovation in the United States (backed up by federal support for basic science) see the government's role as limited because private sector firms have sufficient incentives to invest in socially desirable rates of innovation. Individuals who believe that the U.S. innovation ecosystem is more complex and that business innovates with the help of many other institutions see a more involved role for the government. They believe that technological progress depends on certain infrastructure investments and on specific innovations that are too risky, too complex, or too interdependent with other breakthroughs for private firms to risk the substantial investments that are needed.[3]

Given the importance of the questions of where innovation comes from and what role, if any, government has played in the development of innovations, it is perhaps surprising that relatively little empirical evidence has been brought to bear on them. This report sheds new light on the subject by exploring the sources of key innovations in the U.S. economy over the past four decades. Specifically, we analyze a sample of innovations recognized by *R&D Magazine* as being among the top 100 innovations of the year over the last 40 years to determine where innovations come from and what role, if any, the federal government has played in their development. If the "business-only" account of the development of innovations is valid, we would expect to find that the governmental role is marginal in the innovations recognized in the R&D 100 Awards; if the "partnership" account is accurate, we would expect to see signs of a substantial government role in these innovations.

The U.S. innovation system today is much more collaborative that it was several decades ago and the federal government is playing a much more supportive and important role in innovation.

In the discussion that follows, the report first presents an overview of what is already known about how the U.S. innovation system has changed in recent decades, noting changes in the place of scientific knowledge in the economy, the innovation strategies pursued by large corporations, and government technology policies. Subsequently, the report analyzes data from a sample of R&D 100 Awards over the last 40 years.

This analysis of these data reinforces the idea that the U.S. innovation system has changed in significant ways in recent decades. Whereas the lion's share of the R&D 100 Award-winning U.S. innovations in the 1970s came from corporations acting on their own, most of the R&D 100 Award-winning U.S. innovations in the last two decades have come from partnerships involving business and government, including federal labs and federally funded university research. Indeed, in the 1970s, approximately 80 percent of the award-winning U.S. innovations were from large firms acting on their own. Today, approximately two-thirds of the award-winning U.S. innovations involve some kind of interorganizational collaboration—a situation that reflects the more collaborative nature of the innovation process and the greater role in private sector innovation by government agencies, federal laboratories, and research universities.

In short, for better or worse, the U.S. innovation system today is much more collaborative than it was several decades ago and the federal government is playing a much more supportive and important role in innovation. Several factors explain this phenomenon: (1) growing global competition is shrinking technology life cycles; (2) the complexity of emerging technologies is beyond the internal R&D capabilities of even the largest firms; (3) the expansion of R&D capability in more industries is causing R&D investment to spread vertically in high-tech supply chains, which increases the potential for the loss of value added from a single domestic economy; and (4) a growing number of nations are responding to these trends by implementing new mechanisms that increase the efficiency of R&D.[4]

The old distinction between "basic science" and "applied science" is becoming obsolete, if it ever was relevant.

These findings have significant implications for U.S. economic and innovation policy. To succeed in the future, U.S. innovation policy must help support and reinforce our natural national advantage in collaboration.[5] Thus, funding for the U.S. government's technology initiatives must be expanded and made more secure, and the coordination of these technology initiatives across the federal government, particularly those that support partnerships between firms, universities, federal laboratories, and state governments must be improved.

OVERVIEW OF CHANGES IN THE U.S. INNOVATION SYSTEM

In recent decades, there have been significant changes in the place of scientific knowledge in the U.S. economy, the innovation strategies pursued by large U.S. corporations, and the federal government's technology policies.

Changes in the Place of Scientific Knowledge in the U.S. Economy

In the 1960s and 1970s, many observers came to see that scientific knowledge was becoming ever more central to economic activity.[6] Some regarded the growing visibility of mainframe computers in the U.S. economy as emblematic of the importance of technical expertise, and they correctly predicted a further intensification of the economy's dependence on highly specialized forms of scientific and technological training. A series of breakthroughs in molecular biology in the 1960s and 1970s helped drive innovation in the pharmaceutical and agricultural technologies industries. Subsequent recent advances in material sciences—often relying on the manipulation of compounds at the molecular level—began reshaping how familiar products such as airplanes, automobiles, construction materials, and textiles are made. And the development of semiconductors and a host of related information technologies began driving what later become the information technology revolution of the 1990s and 2000s.

The important point is not simply the growing importance of scientific knowledge for the innovation process in the U.S. economy in recent decades, however, but that sophisticated technological advances have increasingly required close cooperation within multidisciplinary teams that bring together different types of expertise. The development of new software, for example, often requires collaboration between those who are expert in computer languages, those who are knowledgeable about the human-computer interface, and those with domain expertise in the area of the software application. Similarly, cutting-edge projects in nanotechnology, such as developing tiny cameras that can float through the bloodstream, require teams with expertise in biology, chemistry, and physics. Multidisciplinary teams also have to bridge the divide between abstract knowledge and concrete knowledge. If, for example, one member of the team is able to conceptualize a three-dimensional part that would solve a particular problem, then other members of the team have to figure out how that part can be made.

In many ways, the old distinction between "basic science" and "applied science" is becoming obsolete, if it ever was relevant.[7] It is increasingly difficult to "invent" something without first having developed the scientific basis for the invention, and it is also difficult to go from science to innovation without substantial "proof of concept" and supporting "generic" or "platform technologies." In computer science, for example, figuring out how to get more microcircuits on a chip is both a basic and an applied problem. Moreover, in fields such as molecular biology or nanotechnology, progress in solving practical problems can have profound theoretical implications for the understanding of basic scientific questions.

There is, in short, a high degree of consensus that successful technological innovation now requires the assembly and management of multidisciplinary teams that bring together different types of expertise. To be sure, there are still occasional stories of sole practitioners tinkering in their laboratories who suddenly experience a "Eureka moment." But upon deeper probing, some of these stories turn out to be relatively cynical exercises in self promotion. Although "Eureka moments" certainly still come, they tend to be embedded within teams where multiple participants make key contributions. Moreover, even after those individual epiphanies, it often takes months or years of joint effort to turn the breakthrough idea into a working reality.

Changes in the U.S. Corporate Environment and Practices

In the first two decades after World War II, many economic sectors of the U.S. economy were dominated by small numbers of large entrenched corporations. AT&T enjoyed a monopoly over virtually the entire telephone industry, and the "Big Three" auto companies were paralleled by the three broadcast networks that accounted for the great bulk of television advertising dollars. In this era of "oligopoly capitalism," competition by foreign firms for the huge domestic U.S. market was relatively insignificant because few of these firms were able to operate on a scale similar to that of U.S. big business.

Because price competition was far more limited in the two decades after World War II than it is in today's market environment, innovations were a way that firms could charge premium prices or even gain market share from their competitors. With constrained competition and consequent market control, firms were willing to take on the higher levels of risk required to pursue more radical but higher payoff technologies. As a result, many of the dominant firms in the United States used the steady flow of profits to invest heavily in their own research laboratories. They created factories for inventions that brought large numbers of scientists and engineers directly under the corporate umbrella. In the 1950s and 1960s, the central research laboratories of firms such as AT&T, General Electric, IBM, RCA, and Xerox were corporate jewels that attracted highly productive researchers. In retrospect, we know that some firms failed to exploit radical innovations developed in their own labs, but the point is that they financed the laboratories and often gave scientists and engineers considerable latitude to consider projects with no immediate commercial prospects.

This era of oligopoly capitalism came to an end during the 1970s as many of these dominant U.S. firms faced five challenges that would play out over the next several decades. Although the impact of particular challenges varied across industries, the cumulative impact of all the challenges produced dramatic shifts in corporate behavior.

The first challenge for large U.S. firms during the 1970s was mounting competition from foreign firms. This was exemplified by the Japanese competition to the U.S. automobile industry. The second challenge was shifts in government regulatory policies that dismantled significant barriers to competition for entrenched firms. The paradigmatic case was the breakup of AT&T's telephone monopoly, but similar changes occurred in air transportation, television, trucking, and financial institutions. The third challenge was the impact of computerization that over time subjected increasing numbers of firms to competition from unforeseen directions. When IBM signed its first contract with Bill Gates to develop an operating system for its first personal computer, its executives failed to understand that Microsoft would become IBM's most dangerous rival.

The fourth challenge for large U.S. firms was shifts in consumer taste away from standardized products that had the effect of dissolving mass markets into a series of niche markets and the concomitant rise of information technologies that let firms produce efficiently for smaller, niche markets. This transformation was exemplified by the challenge to Sears and other retailers who had long served a fairly undifferentiated mass market. The fifth challenge for large U.S. firms was shifts within the financial markets that placed increasing pressure on large corporations to prioritize increasing short-term returns to shareholders over growth or other objectives.[8] Even some of the largest firms faced the risk of a hostile takeover if they failed to respond to the concerns of increasingly aggressive institutional investors.

The responses of large U.S. firms to these five challenges that arose in the 1970s are familiar. Large firms cut out many layers of middle managers in an effort to become leaner and quicker in responding to market changes. They got rid of units and divisions that were not operating at high levels of effectiveness and they moved to outsource functions that could be performed more cheaply by other firms. They adopted tough new metrics to ensure that new investments in plant and equipment were likely to have a significant impact on the firm's profits.[9]

These corporate transformations produced three types of adaptation in the realm of R&D. Some large U.S. firms simply closed down laboratories or significantly cut back the size of their in-house R&D operations. But in those industries in which it is risky to function with diminished R&D capacity, many large firms responded with initiatives designed to enhance the productivity of R&D operations. Thus, some large U.S. firms imposed a tighter reign on technologists to keep them from spending time on "blue sky" projects whose fruits might lie in the distant future. Some firms also focused more attention on the development end of R&D, such as devising small improvements designed to increase the marketability or profitability of existing products. Finally, as the findings below reinforce, many large U.S. firms responded by greater outsourcing of R&D operations to either domestic or foreign laboratories, partnering with other organizations including universities and government laboratories, or relying on acquisitions of small firms as the way to maintain a pipeline of new products.[10] Although total industry R&D spending in the United States is now twice as great as federal R&D spending, there is cause for concern about the capacity of such spending to generate significant innovations and about whether such spending will continue to grow in the future as it did in the past.

Changes in U.S. Government Policies and Practices

In the United States during the three decades immediately following World War II, the federal government accounted for 2/3 of all R&D spending as contrasted to 1/3 in recent decades.[11] However, the government effort was heavily concentrated on military and space imperatives. Familiar spinoffs such as mainframe computers and jet airplanes had been largely unintended consequence of federal government spending for the military and the space program—spending in support of research in these areas and for procurement of products using these technologies.[12]

In the 1980s, however, the federal government's policies changed in direct response to the heightened international competitive pressures experienced by U.S. corporations. In that decade, both Congress and the executive branch launched a series of initiatives that were intended to mobilize public resources to accelerate the development and commercial exploitation of new technologies. These federal programs extended well beyond the defense and space sectors that had previously been the main areas of federal technology policy.[13]

The federal initiatives launched in the 1980s can be usefully grouped into four separate domains, in which there is deliberate overlap. First was a series of efforts to increase the commercial impact of research already being funded by the federal government, particularly in universities and government laboratories. Federal incentives were created for scientists and institutions to push their research discoveries into the commercial sphere either by creating new startups, licensing technologies to private firms, or engaging in collaborative projects with business firms. The Bayh-Dole Act encouraged universities to see their research enterprise as a potential revenue source and concerted efforts were made over 20 years to shift resources in the federal laboratories away from weapons production and towards commercial applications.

Second, new federal programs were created in the 1980s to help finance precompetitive R&D costs for individual firms, both startup and established firms.[14] Most prominent among these programs is the Small Business Innovation Research (SBIR) program through which federal government agencies set aside a small percentage of their R&D budgets for projects proposed by small firms, many of which are newly created spinoffs from university or federal laboratories. The Advanced Technology Program at the National Institute of Standards[15] and a series of initiatives at the Department of Energy provided matching funds to support particularly promising new technologies among both new and more established firms.

Third was an expansion in the 1980s and early 1990s of the federal government's technical support to business firms trying to surmount technological barriers. The Manufacturing Extension Program, for example, has helped thousands of small firms adapt to computerization and the more demanding schedules of just-in-time production. The National Nanotechnology Initiative has made a series of federally funded, university-based laboratories available to business firms that want to avoid the costs of developing their own laboratory infrastructure. Similarly, efforts by federal laboratories to form partnerships with firms provide them with important technical support, through the formation of cooperative R&D and Work For Others agreements.

Fourth were federal government initiatives to facilitate and support research consortia that bring together multiple firms in the same industry to solve technological problems. The paradigm for these was the substantial federal investment in SEMATECH in the 1980s.[16] With the federal government's support, the U.S.-based semiconductor industry modernized its own supplier firms and carried out a sophisticated research agenda that helped the industry stay ahead of foreign competitors. A variety of government agencies, including the Department of Energy, National Institute of Standards and Technology through the Advanced Technology Program, and various branches of the military have followed this example to convene and support large-scale industrial consortia to overcome technological challenges. At the same time, the National Science Foundation and the military have supported a more decentralized system of university laboratories in the United States that build more localized networks of collaboration with groups of industrial partners. The National Science Foundation's Engineering Research Centers, for example, are a group of 17 interdisciplinary centers located at universities and operated in close partnership with industry.

Some observers have argued that these federal initiatives launched in the 1980s coalesce into a system or a triple helix of university-industry-government collaboration that has become central for innovation.[17] Other observers are more skeptical. Some emphasize the "pork barrel" side of the picture, arguing that Congress is simply trying to expand the flow of federal R&D funds into members' districts with little attention to the efficacy of these efforts. Others decry the extreme decentralization and lack of coordination that create the danger of multiple, expensive, and independent interventions to overcome a particular technological barrier.

Given the longstanding problem of developing effective measures of the sources of U.S. innovation, these disagreements have continued with little prospect for resolution. One side mobilizes anecdotes about federal outlays that were critical in launching firms that championed significant new technologies, but these are easily countered with reports of "laboratories to nowhere" set up by congressional earmarks to bring dollars and jobs to colleges that might not otherwise receive federal support. By assembling and analyzing a unique set of data on award-winning technologies that spans the past four decades, this report sheds new light on these debates.

UNDERSTANDING THE DATA ON INNOVATIONS

Each year since 1963, *R&D Magazine* has recognized the 100 best inventions that are incorporated into commercial products.[18] The R&D 100 Awards carry considerable prestige within the community of R&D professionals and are comparable to the Oscars for the motion picture industry. Organizations nominate their own innovations. All entries are initially evaluated by outside juries that include representatives of business, government, and universities. After considering the outside juries' votes, the editors of *R&D Magazine* decide on the final list of awards.

With only 100 innovations to be recognized by the R&D 100 Awards each year, juries are instructed to recognize the full diversity of innovative activity, not to focus solely on dynamic sectors such as electronics or biotechnology. The diversity of innovative activity is well represented every year of the R&D 100 Awards. In 2006, for example, awards were given in 17 categories, including areas such as energy- and environment-related technologies, computer software, analytical instruments, and laser technologies. Award winners included innovations pertaining to common consumer goods (advances in lithium ion battery technologies and automobile steering systems), as well as relatively specialized laboratory equipment (spectrometry equipment, or software used for "3-D modeling of charged particle beam devices"); from a plethora of technologies related to fields that have recently gained widespread media coverage—such as nanotechnology and genomic sequencing—to advances in long-established (but no less technically complex) fields such microscopy and semiconductors. Past winners of R&D 100 Awards include "Polacolor film (1963), the flashcube (1965), the automated teller machine (1973), the halogen lamp (1974), the fax machine (1975), the liquid crystal display (1980), the printer (1986), the Kodak Photo CD (1991), the Nicoderm antismoking patch (1992), Taxol anticancer drug (1993), lab on a chip (1996), and HDTV (1998)."

The R&D 100 Award winners are only a small portion of a much larger universe of nominated innovations, and we think that a careful analysis of the winning U.S. innovations is an excellent window into the U.S. innovation system. To identify the types of organizations that were responsible for nurturing these award-winning technologies, we coded all of the R&D 100 Award winning innovations for three randomly chosen years in each of the last four decades: 1971, 1975, 1979, 1982, 1984, 1988, 1991, 1995, 1997, 2002, 2004, and 2006.

The R&D 100 Awards sample is by no means a random sample of innovations in any given year; rather it is an opportunistic sample. Social scientists often take advantage of opportunistic samples in situations like this, where it is overwhelmingly difficult to identify the full universe of innovations from which one would want to draw a random sample.[19] Before describing our analysis of this data set, it is important to explore what kinds of innovations the data set is more likely to recognize.

The process for identifying recipients of the R&D 100 Awards is inevitably tilted towards product innovations rather than process innovations designed to raise the efficiency of the production process for goods and services. Some process innovations, such as a new type of machine tool or a more advanced computer program for managing inventories, might be recognized, but many important process innovations involve complex combinations of new equipment and new organizational practices. The process for identifying recipients of the R&D 100 Awards is also biased against military innovations, because cutting-edge weapons are usually shrouded in secrecy and unavailable for purchase. Given that the great bulk of federal R&D dollars in the United States are directed towards weapons systems, one has to assume that many government-funded innovations lie outside of this competition.

In addition, the R&D 100 Awards are biased in favor of the kinds of "cool gizmos" that engineers love rather than towards less fancy innovations that might have a broader market. This bias is nothing new, however; it has been a constant feature of these awards from the beginning. R&D professionals can be expected to use evaluative criteria different from those used by economists or the general public, and even with this bias, the award winners are still a very useful opportunistic sample.

Other biases might also enter the R&D 100 Awards process. Questionable decisions and politics will always be a factor as jury members seek to reward friends and deny recognition to enemies. But for our purposes, it is not necessary that these awards recognize the very best innovations of any particular year. All that is necessary is that the awardees represent a reasonable sample of the strong innovations available for recognition and that there is not a consistent bias that favors awardees of a particular type. Moreover, by looking at averages by decade, we have tried to adjust for year-to-year fluctuations in the biases of the juries.

In looking at other studies of awards, the different resources that organizations have to prepare their nomination materials are an obvious source of bias. Big architectural firms, for example, can hire the best photographers and devote considerable resources to a nomination while the hard-pressed solo practitioner might throw the application form together in a few hours. There could be a similar bias in the R&D 100 Awards, with larger corporations having more expertise at putting together persuasive nomination packets, but the magnitude of this bias would be limited for several reasons.

First, the universe of applicants for the R&D 100 Awards is limited to organizations that have actually developed a commercial product, and since winning the award is a powerful form of advertising, even the tiniest firms have strong incentives to devote resources to an effective application. Likewise, universities and federal labs have an incentive to apply, if for no other reason than to help improve their reputations and for contributing to economic growth. Second, the quality of "coolness" that engineers and technologists admire in a product is substantially easier to convey in words than the more abstract, aesthetic qualities that architectural or film juries might be rewarding. And over the years, many firms have been one-time R&D 100 Awards winners—an observation that reinforces the impression that it is the quality of the product and not the quality of the nomination packet that wins awards. Finally, it is difficult to imagine any reason that R&D Magazine and the juries would prefer submissions that originated in public labs over those from private labs, or vice versa. The criterion that the product actually is available for sale is a great equalizer; it means that the awards are not recognizing abstract ideas but actual saleable products.[20] Thus, when the data show a dramatic rise over time in the percentage of awardees that originate in publicly financed laboratories, there is little reason to disbelieve this finding as an artifact of some methodological shortcomings in the awards process.

The R&D 100 Awards tell us little about the more distant ancestry of a particular innovation. The producers of a winning product might be paying licensing fees to the patent holders on 20 previous innovations on which their product builds. Some of those predecessors might be on the other side of the world and others might be working in the office next door. Similarly, they might have been university-based or industry-based researchers. It is only through very detailed case study analyses that it is possible to understand the larger universe of antecedents or ancestors for any particular innovation.

A different metaphor might make it easier to understand the implications of using this data set. The R&D 100 Awards for the 100 top innovations in a given year recognize just the tip of the proverbial iceberg—that is, the most recent steps in the innovation process. The many earlier innovations on which the award winner depends are submerged and out of sight. We are assuming that the tip provides the best possible case for recognizing the private sector's role in innovation since it focuses on commercially available products. Studies that trace out the genealogy of particular innovations strongly suggest that the more foundational inventions tend to occur in university laboratories.[21]

Nevertheless, coding the R&D 100 Awards data does present some challenges because the information reported to R&D Magazine is inevitably incomplete. The magazine follows what is in the nomination materials and credits the organization or organizations that developed each particular innovation,[22] but it does not concern itself with questions of funding. If, for example, a major defense contractor is credited with an innovation while fulfilling a military contract, the Defense Department's role will not be noted—even if there was considerable guidance and support from Pentagon scientists. Similarly, if a small startup developed its innovation with funding from the federally funded Small Business Innovation Research (SBIR) program, that information is also omitted. However, we have adjusted for this latter problem by independently determining which of the winners have been supported by the SBIR program.

ANALYSIS OF ORGANIZATIONAL AUSPICES AND FUNDING FOR TOP INNOVATIONS

The analysis of organizational auspices and funding sources for the 1,200 innovations in the 12 randomly selected *R&D Magazine* competitions from 1971 to 2006 is described below. Ideally, we would have liked to code both the organizational auspices and the funding sources for every innovation awarded an R&D 100 Award in the 12 competitions that we analyze. Organizational auspices for the innovations can be established with a fairly high degree of accuracy with a reasonable amount of research, so for each of the innovations in our sample, we coded the organizational auspices as completely as possible. This process required additional research to classify the different types of business firms that were credited with particular innovations.

Figuring out the funding source for all the innovations awarded an R&D 100 Award in the sample is an almost impossible task. The primary reason for the difficulty is that tracking flows of federal support to businesses is laborious and complicated.[23] In the last few years, a watchdog group has established a database that makes it possible to find out all of the different government contracts and grants awarded to a particular corporation, but that service only covers the period from 2000 forward. Before that, tracking federal grants and contracts requires proceeding agency by agency and, even then the published sources are incomplete.[24] Our approach to figuring out the funding, therefore, represents a compromise.

Analysis of Data on Organizational Auspices of Innovations in Our Sample

Our analysis showed that the innovations awarded R&D 100 Awards in the 12 randomly selected *R&D Magazine* competitions from 1971 to 2006 originated from three broad categories of organizational auspices:

- PRIVATE AUSPICES in the United States

  1. Fortune 500 firms operating alone.[25]

  2. Other firms operating on their own. This is a residual category that includes small and medium-sized firms and firms that are difficult to classify.

  3. Collaborations among two or more private firms with no listed public sector or nonprofit partner. Industrial consortia are included in this category.[26]

- PUBLIC OR MIXED AUSPICES in the United States

  4. Supported spinoffs. These are recently established (less than 10 years from founding) firms started by technologists at universities or government labs who have been supported by federal research funds. Although there are a number of firms which appear or reappear as award-winners more than a decade after being spun off from a government program or university, we set a 10-year window to reasonably capture the fact over the course of a decade, technology-based firms must typically go well beyond their original innovations and resource-supports to remain viable. Spinoff firms that continued to win awards after their first decade of operations were thus coded as "other firms" or, in the case of Scientific Analysis International Corporation, as a Fortune 500 firm.

  5. Federal laboratories—working by themselves or in collaboration. Most of these innovations come from the federal laboratories run by the Department of Energy, but some come from the National Institutes of Health, military laboratories, and labs run by other agencies. If a university is a partner in one of these collaborations with a laboratory, it will be reported here and not under university.

  6. Universities—working by themselves or in collaboration with entities other than federal labs.

  7. Other public sector and nonprofit agencies—working by themselves or in collaboration with private firms.

- FOREIGN AUSPICES

  8. Foreign firms. Because we were focusing on the U.S. innovation system, we generally excluded innovations attributed to foreign firms from our sample. The only exceptions occur when the foreign firm collaborated with a U.S. partner or the foreign firm owns a large, established U.S. business, such as Daimler Benz' ownership of Chrysler. In such cases, we code the firm as a Fortune 500 firm.[27]

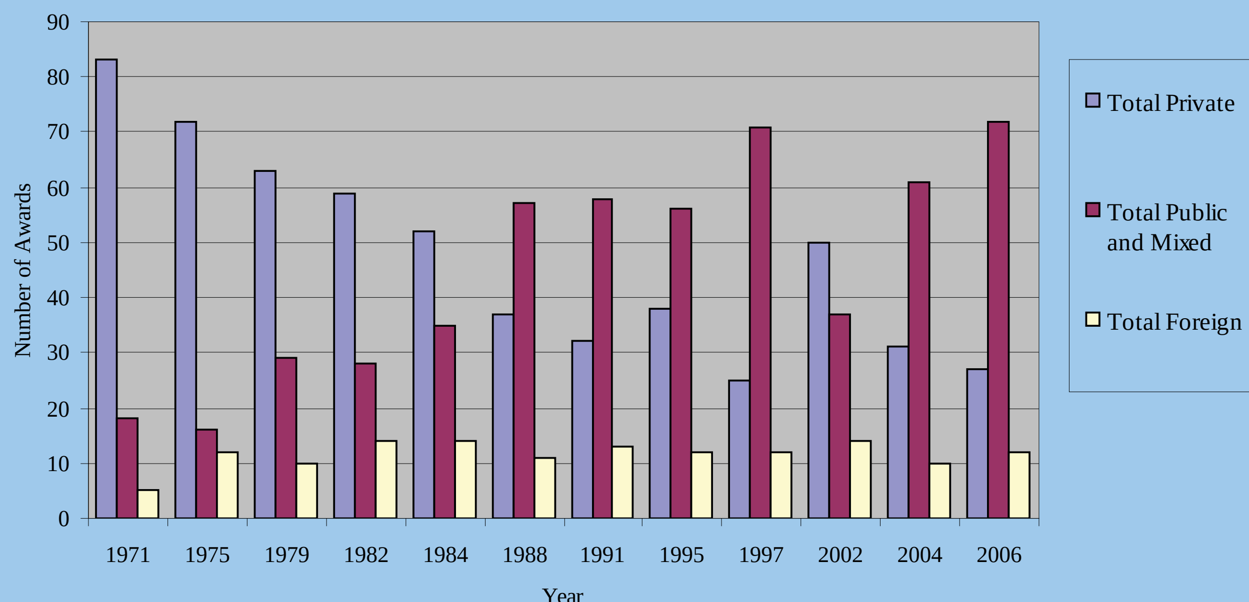
The overall trend in the number of R&D 100 Awards for the three broad categories of organizational auspices for the 12 years considered is shown in Figure 1. Since 1975, the number of R&D 100 Awards won by foreign firms has remained relatively constant at 10 to 14 per year, with only minor fluctuations from year to year. Among U.S. innovations that were R&D 100 Award winners, there has been a dramatic shift in organizational auspices from 1971 to 2006—from private auspices to public or mixed auspices. In 1971, 83 out of 97 (86 percent) U.S. innovations that received an R&D 100 Award were developed under completely private auspices; in 2006, only 27 out of 88 (31 percent) were developed under completely private auspices. The shift occurs gradually, but from 1988 onward, public and mixed auspices come to dominate the U.S. innovations receiving R&D 100 Awards.

An even more dramatic transformation—the declining weight of the Fortune 500 firms among U.S. innovations receiving R&D 100 Awards—is depicted in Figure 2. This figure shows both awards attributed to Fortune 500 firms operating alone or in collaboration with partners, both public and private. At the beginning of the period, Fortune 500 corporations were the dominant force in the U.S. competition, but recently, they have become relatively minor participants. In 2006, only two awards could be attributed to the solo efforts of Fortune 500 companies.

Figure 3 shows the number of U.S. innovations receiving R&D 100 Awards disaggregated by the different elements of the broad category public and mixed auspices—supported spinoffs, government laboratories, universities, and other public sector and nonprofit agencies. In the last 20 years, federal laboratories have become the dominant organizational locus for wining R&D 100 Awards (although as noted earlier, in most cases federal labs are working with either firms and universities, or both). Federal laboratories now have about the same weight in the R&D 100 Awards won by U.S. firms as the Fortune 500 firms did in the 1970s—averaging about 35 awards per year. This finding is surprising because many observers hold the federal laboratories in low esteem and doubt their capacity to contribute to innovation.

Most of the innovations from federal laboratories originate in the Department of Energy laboratories that were initially created to develop atomic weapons in the

Figure 1: Innovation Awards for U.S. Private, U.S. Public and Mixed, Foreign Organizations

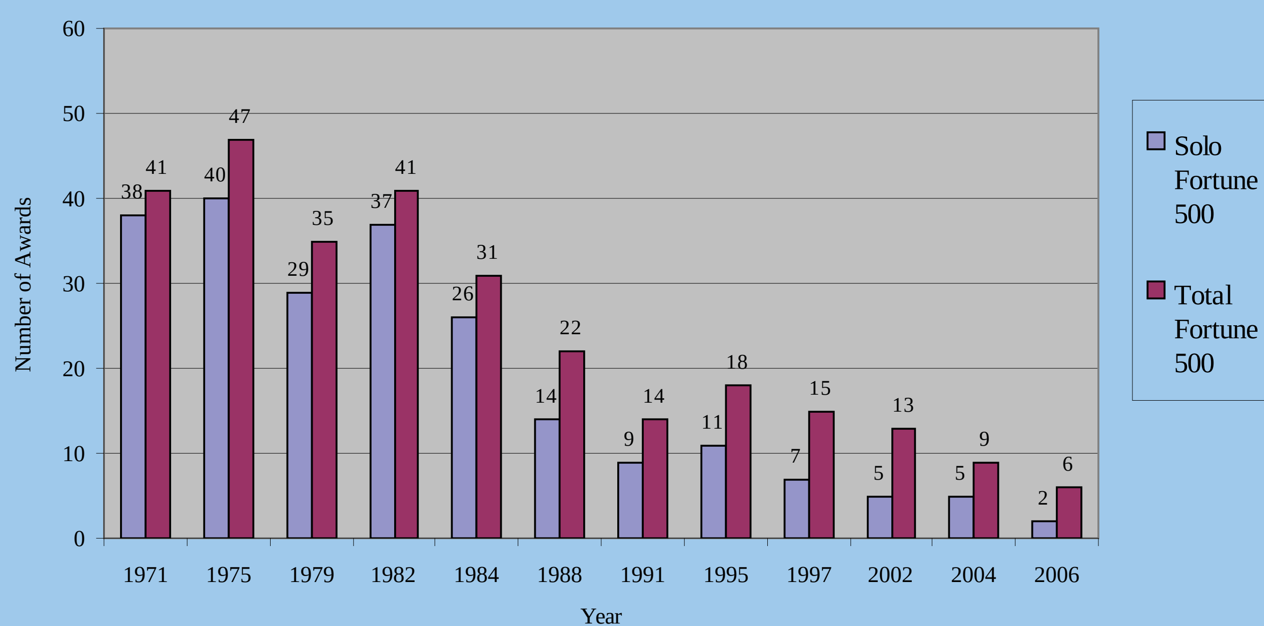


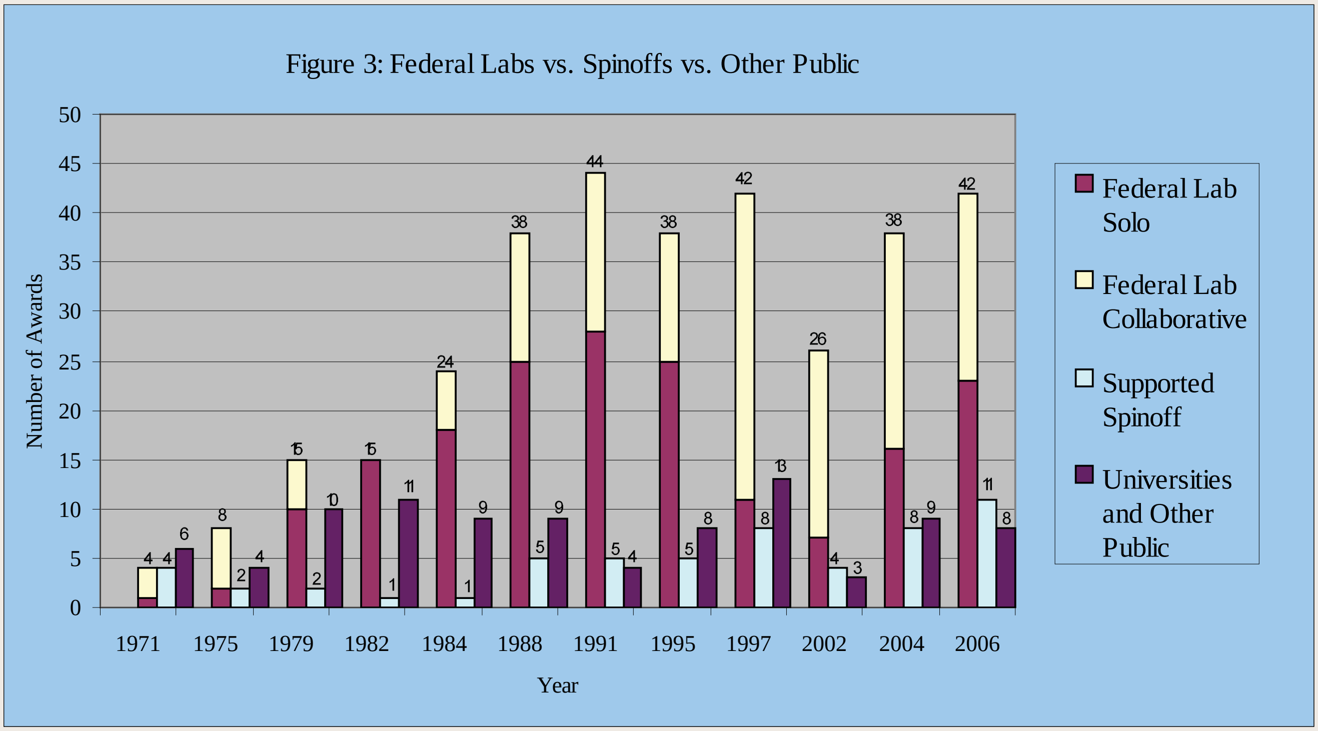
early years of the Cold War. In 2006, for example, the Lawrence Livermore National Laboratory won seven R&D 100 Awards. Two of its award-winning innovations were developed entirely by the lab itself; a software program called Babel that seamlessly translates from one computer language to another and another program for data mining. A third award-winning innovation, developed in collaboration with a University of California at Berkeley scientist, dramatically cuts the cost of using existing telescopes to search the universe for undiscovered planets. The other four award-winning innovations were developed in collaboration with small and medium-sized firms. One of the four innovations is a wavelength converter for lasers. The other three innovations are all relevant to diminishing the threat of terrorism; they include small instruments to detect explosives or nuclear materials and an automated surveillance system.

In some cases, *R&D Magazine* attributes an innovation entirely to a federal laboratory. This means that the laboratory has licensed the product to a commercial firm that is not credited for the innovation, presumably because they entered the picture after all the technical problems were solved. In other cases, the magazine credits both a federal laboratory and one or more partners, who might be university researchers, private firms, or a combination of the two. A 2006 R&D 100 Award given to the Oak Ridge Lab for a metal infusion surface treatment, for instance, had no fewer than 14 institutional partners including small and large firms and scientists from the University of Tennessee. The historical trend, with some year-to-year fluctuation, has been for an increasing share of R&D 100 Awards for U.S. innovations involving federal laboratories to be in recognition of collaborative projects with private firms, universities, and/or spinoff firms that market technologies developed in the labs or with the cooperation of lab scientists rather than solo projects developed entirely by a federal laboratory.

After federal laboratories, the dominant organizational locus for wining R&D 100 Awards in the public or mixed auspices category in the United States is supported spinoffs. Supported spinoffs, on their own, averaged close to eight awards per year in the current decade; they also won some additional awards in partnership with government laboratories or universities. In our analysis, we counted a firm as a spinoff only if it won a R&D 100 Award for an innovation within 10

Figure 2: Solo Fortune 500 vs. Total Fortune 500





years of its founding. Thus, our count understates the number of firms with award-winning innovations that received substantial initial support from public agencies or resources. The typical pattern for a spinoff firm is that a professor or a scientist at a university or federal laboratory makes an important discovery and consults with university or lab officials as to how best to protect the resulting intellectual property. The usual path is that the organization encourages the innovator to start his or her own firm to develop and ultimately market the new product. The more entrepreneurial universities and laboratories function almost as venture capitalists helping the individual find investors and experienced managers who could guide the firm.[28]

The final category in Figure 3 encompasses the number of R&D 100 Awards won for innovations by universities and other public sector agencies and nonprofit firms. Surprisingly, the direct weight of universities among award winners is relatively modest. There are several reasons for this situation. One is that many university-produced innovations are coded under the supported spinoffs category. Another reason is that university-based researchers are increasingly part of collaborations with federal laboratories, and our coding system attributes those innovations to the labs.

In Figure 4, we correct for this situation by showing the number of R&D 100 Award-winning innovations in the United States in whose development universities participated. The numbers of award-winning innovations involving universities as participants are certainly not insignificant, but they are much lower than the number of award-winning innovations involving federal laboratories. Even though scientific discoveries at universities have become ever more central to the innovation process, most of the transition into commercial products is mediated through spinoffs and the activities at federal laboratories. When a university researcher decides to move beyond generic technical knowledge to develop a prototype of a new product, he or she usually does this through a collaboration with a business firm.

The increasing number of R&D 100 Award-winning innovations awarded to interorganizational collaborations seen in Figure 5 is even more dramatic than the shift from the private sector to the public sector shift revealed in Figure 1. The number of innovations attributed to a single private sector firm operating alone averaged 67 in the 1970s, but it dropped to an average of only 27 in this decade. (We have coded all of the award-winning public sector innovations as interorganizational because they all ultimately involve working with a commercial partner to develop and market the product.) The growing importance of interorganizational collaborations shown in Figure 5 provides powerful support for those scholars who have emphasized the centrality of networks to contemporary innovation processes.[29]

The number of award-winning innovations from public sector entities increased dramatically from 14 in 1975 to 61 in 2006.

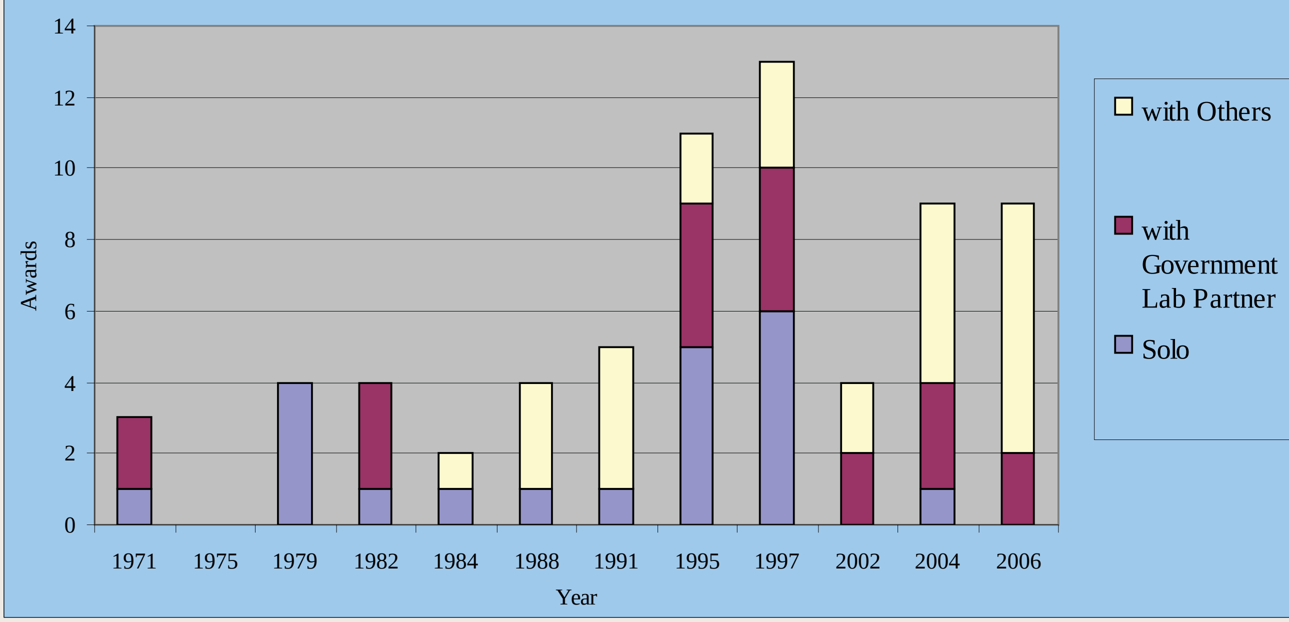
There are several reasons for this kind of systematic interorganizational cooperation. The most obvious is that assembling all of the relevant forms of expertise under a single organizational roof is impractical and expensive. But this reason cannot explain everything, because organizations could also bring in people with the expertise that they need on a temporary basis as consultants or contract workers. Those kinds of temporary arrangements would not show up in this data as actual interorganizational cooperation in which the innovation is credited to several distinct organizations.

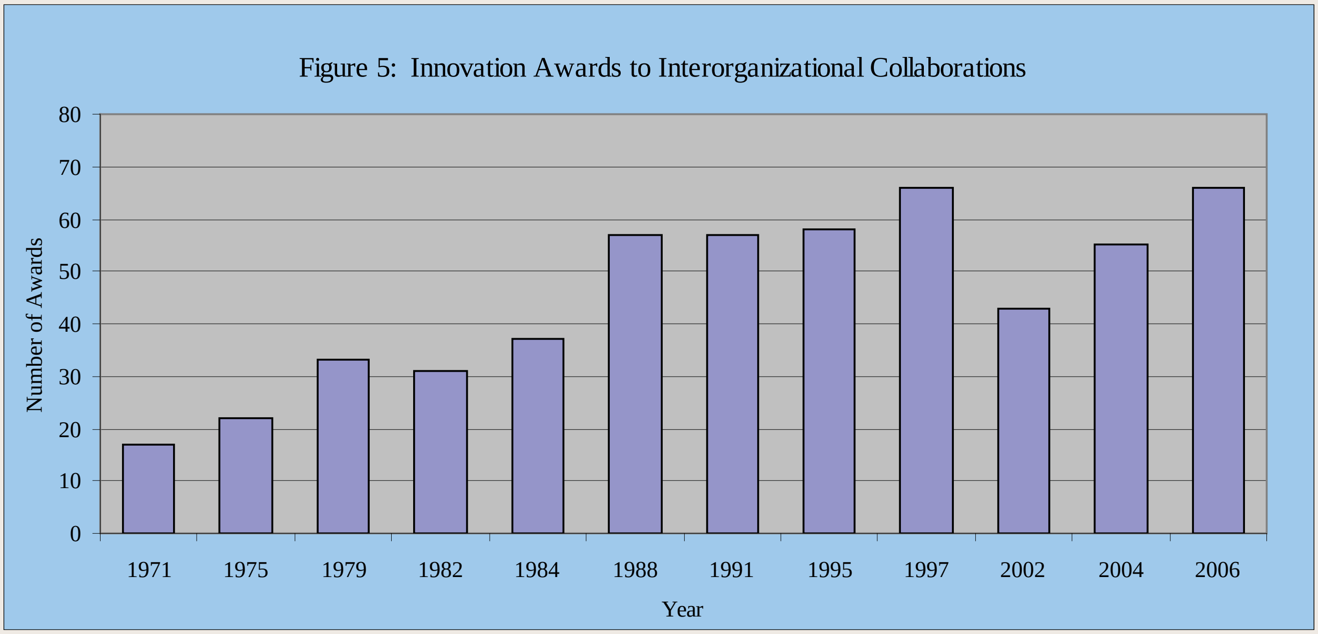
A second reason has been suggested in the literature—namely, the idea that the connections between the knowledge embodied in one organization and the knowledge embodied in one or more other organization are most critical for the innovation process. It is the sparks generated when these different approaches are combined that facilitate effective new approaches.[30]

One element here is the relationship between organizational hierarchy and innovation. Effective innovation almost always requires thinking outside the box, and it can be difficult to persuade supervisors to provide the needed resources of employee time and money that are involved in pursuing a path that is inevitably uncertain. Obviously, the more collegial structures of universities and government laboratories are designed to minimize this hierarchical constraint by giving researchers more freedom to pursue ideas that are outside the box.

Research efforts that involve cooperation between two or more different organizations similarly weaken this hierarchical constraint on thinking outside the box. Technologists from a private sector firm have to

Figure 4: Innovation Awards to Universities Working Solo and in Collaboration





get permission from their supervisors to work in collaboration with researchers at a university or a public sector lab. But once that permission has been granted, they tend to gain—at least temporarily—some of the greater autonomy of their new colleagues. In a sense, they gain some academic freedom by virtue of working in collaboration with academics. Moreover, private sector managers cannot subject the whole collaborative effort to the kind of careful monitoring that they employ for in-house projects. And some of this same diminished managerial attention can be expected even when the collaboration is between two private sector firms.

Recently, Lester and Piore have suggested that "collaborative public spaces" are critical to the innovation process because they facilitate the freewheeling discussion and exchange of ideas that make breakthroughs possible.[31] Almost by definition, such "public" spaces are rare inside corporations, but they have been successfully created in private sector collaborations. The more successful industry consortia that have followed the model first established by SEMATECH have been able to bring together researchers from different firms to argue and collaborate on solutions to shared problems with some significant degree of independence from hierarchical control.

Something similar happens in the model of university-industrial collaboration that has been pushed by the National Science Foundation through its Industry University Research Centers and Engineering Research Centers. The National Science Foundation provides entrepreneurial academics with startup funds to create a research center that will advance a technology that could prove useful to business. The scientist or engineer who runs the center then has the responsibility to recruit business sponsors for the center who will be willing to support the center by paying regular dues. Business executives are given a voice in the center's research agenda and are encouraged to send their people to work with the university-based staff on specific problems. In effect, the center itself becomes the collaborative public space for university and industry scientists and engineers.

Analysis of Data on Funding of Innovations

The growing weight of public institutions as the source of U.S. innovations that win R&D 100 Awards and the growing role of interorganizational collaboration in U.S. innovations are suggestive that public funding has become steadily more important to the U.S. innovation process in recent years. Nevertheless, it is necessary to probe a bit further, because the U.S. firms coded as "private" are sometimes recipients of federal funding—sometimes for the precise R&D activity that wins the award.

Back in the 1970s, for example, some of the laboratories of the Fortune 500 firms that were frequent R&D 100 Award winners received substantial amounts of direct federal funding.[32] And in the more recent period, there has been a proliferation of programs through which government agencies support private sector R&D.[33] An example of the latter is the growing importance of Small Business Innovation Research (SBIR) firms among the award winners.

The SBIR program, established in the 1980s, is one of the most important mechanisms through which the federal government supports smaller innovative firms, including the firms that we have labeled as supported spinoffs. The SBIR program is a set-aside program; all government agencies that finance a large amount of R&D must set aside 2.5 percent of their R&D budgets for projects that originate with small businesses. The program awards up to $750,000 in no strings support for projects in Phase I and up to $1.5 million for Phase II projects that have shown significant progress in meeting the initial objectives. Some of the SBIR firms have now been in existence for 20 or more years, and at least one has grown to become a Fortune 500 firm.

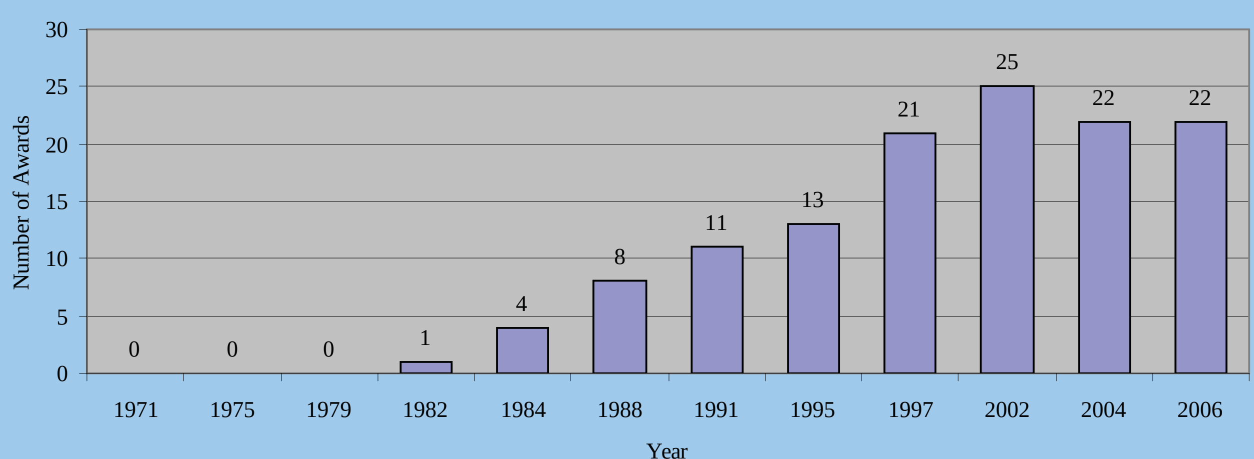
Figure 6 shows the total number of past and present SBIR winners among winners of R&D 100 Awards. The results show that these SBIR-nurtured firms consistently account for a quarter of all U.S. R&D 100 Award winners—a powerful indication that the SBIR program has become a key force in the innovation economy of the United States.

Figure 7 shows a more comprehensive measure of the role of federal financing of R&D 100 Award winners in the United States in 1975 and in 2006. The bottom part of the bar graph for each year shows the number of award-winning innovations from public sector entities in the United States that rely heavily on federal funding. As indicated earlier, the number of award-winning innovations from public sector entities increased dramatically from 14 in 1975 to 61 in 2006.

In 2006, only 11 of the U.S. entities that produced award-winning innovations were not beneficiaries of federal funding.

The top part of the bar graph for each year in Figure 7 shows the number of Fortune 500 and "other" U.S. firms that received at least 1 percent of their revenues from the federal government.[34] The 1 percent screen picks up both large defense contractors and firms that have received substantial federal grants to support their R&D efforts. In 1975, 23 innovations that won R&D 100 Awards were developed by private

Figure 6: Innovation Awards to SBIR Firms



firms in the United States that received at least 1 percent of their revenues from federal support. Prominent among these firms was General Electric, which developed nine of the award-winning innovations that year.[35]

There is evidence that in 2006 the federal government directly funded three of the five private collaborations in the United States that produced innovations that received R&D 100 Awards. Of the 20 "other firms" that won awards in 2006, 13 had federal support above the 1 percent threshold and we were able to link the federal money directly to the specific innovation that received the award. Hence, 16 of these "private" innovations count as federally funded. The overall result in Figure 7 is that the number of federally funded innovations rises from 41 in 1975 to 77 in 2006.

In 2006, only 11 of the U.S. entities that produced award-winning innovations were not beneficiaries of federal funding. And even among this group of 11, there were some ambiguous cases. Dow Automotive won an R&D 100 Award for its work in developing an adhesive used with composite auto parts that was installed in Volkswagen cars. But a few years earlier, Dow had been a beneficiary of a substantial grant from the Advanced Technology Program in the Department of Commerce that was designed to accelerate the use of composites in automobiles. Two other winning firms—Brion Tech and MMR Technologies—were recent spinoffs from Stanford University, but since the firms had not received federal support, they were not coded as "supported spinoffs"; however, it is likely that the professors behind the companies received federal research grants while at Stanford. Finally, we were unable to ascertain whether any of those remaining firms received research support from federal laboratories.

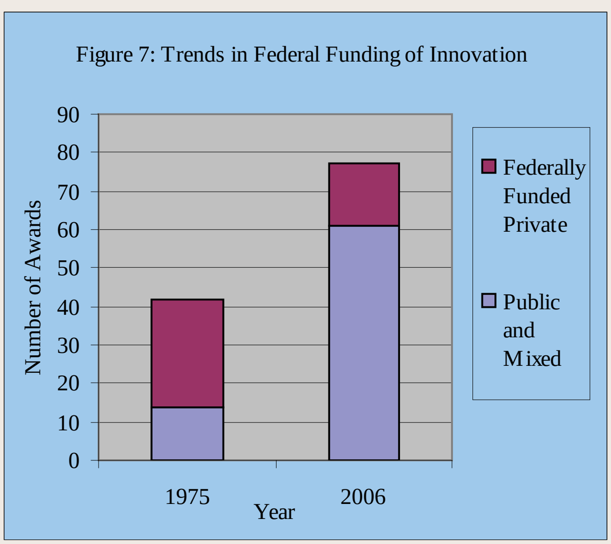


Figure 7: Trends in Federal Funding of Innovation

If one is looking for a golden age in which the private sector did most of the innovating on its own without federal help, one has to go back to the era before World War II.

In short, Figure 7 probably understates the magnitude of the expansion in federal funding for innovations in the United States that won R&D 100 Awards between 1975 and 2006. After all, in 1975, we counted innovations as federally funded even if support was not going to the specific unit of the firm that was working on a particular innovation. For 2006, however, a demonstration of federal support required showing that the federal funds were going to the same unit that was responsible for the particular technology that won the award.

The fundamental point is that even in the period that Fortune 500 corporations dominated the U.S. innovation process, they drew heavily on federal funding support. If one is looking for a golden age in which the private sector did most of the innovating on its own without federal help, one has to go back to the era before World War II. Nevertheless, over the last 40 years, the R&D 100 Awards indicate a dramatic increase in the federal government's centrality to the innovation economy in the United States. In the earlier period, U.S. technology policies were almost entirely monopolized by the military and space programs. More recently, a wide range of federal agencies that are not part of the Department of Defense are involved in supporting private sector R&D initiatives. Key agencies now include the Department of Commerce, Department of Energy, National Institutes of Health, Department of Agriculture, National Science Foundation, and Department of Homeland Security. In addition, over the last 20 years, state governments have become much more involved in technology policy, with many, if not all states funding technology-based economic development activities.[36] To the extent that state programs help small firms or university and federal lab innovations, their role would not be picked up in this analysis.

DISCUSSION

Back in 1887, Thomas Edison built an invention factory that has long been seen as the inspiration for the rise of the corporate research labs established by large U.S. firms during the 20th century. Our analysis suggests that although large corporations in the United States emulated Edison's model for decades, this pattern became much weaker after the corporate reorganizations of the 1970s and 1980s. Thus, the "era of Edison" did not last the full century.

It is not clear why the relative role of Fortune 500 companies in the U.S. innovation system has declined. We can hypothesize three factors. First, it seems likely that big corporations facing relentless pressures from the financial markets have been forced to cut back on expenditures that do not immediately strengthen the bottom line. In some cases, corporate cutbacks have meant eliminating laboratories altogether; in other cases, such cutbacks have meant reducing expenditures on early stage technology development that is often both expensive and risky and is more likely to lead to the kind of radical breakthroughs that win awards like the ones analyzed here

A second factor that may be involved in the decline in Fortune 500 companies in the U.S. innovation system is that several factors, including the rise of computers and the Internet, have made it much easier for small firms to enter markets previously dominated by large firms. Many technologies today require less capital-intensive production processes (e.g., software), making it possible for small firms to innovate the technologies for which they received R&D 100 Awards. In other industries (e.g., biopharmaceuticals), small, innovative companies can contract out manufacturing (e.g., of new drugs). Because small and mid-sized firms can now better compete in product markets, they have dramatically increased their R&D investments. In fact, while the ratio of R&D investments to U.S. gross domestic product more than doubled between 1980 and 2000, almost all of that increase was due to increased R&D investments by small and mid-sized firms with fewer than 5,000 employees.[37] Moreover, large firm R&D may now be more focused on improving existing product lines, as opposed to generating radically new innovations.

The third factor that may have contributed to the decline of Fortune 500 companies dynamic is a change in the employment preferences of scientists and engineers. As the employment landscape has shifted, it seems quite possible that many talented scientists and engineers have voted with their feet and have left work in corporate labs in favor of work at government labs, university labs, or smaller firms. More research is necessary to tease out the causes.

But returning to the history of the Edison lab suggests a longer term and more structural explanation for the recent shifts in the U.S. innovation system that we have uncovered. Revisionist scholars have discovered that Edison's laboratory actually operated differently from the corporate labs of the 20th century.[38] It is true that Edison assembled a team of scientists and engineers that had built up considerable expertise in working with electrical devices—but Edison's team divided its time between internal projects and external projects. The Edison laboratory did extensive contract work for other firms, helping them develop solutions to particular problems that their industry faced. Edison's employees worked closely with employees with technical knowledge from those other firms.

The argument by revisionist historians is that the extraordinary productivity of the Edison labs was a result of the systematic interaction between Edison's team and other groups of experts with very specific types of knowledge. When U.S. corporations sought to emulate Edison's model in the 20th century, though, they built elaborate laboratories that tended to cut their in-house technologists off from these systematic encounters with experts in other organizations. This choice fit with the model of the corporation that was exemplified by Henry Ford's decision to produce his own steel at the River Rouge plant. The idea was that bringing these activities, including R&D, fully in-house maximized management's ability to deploy the organization's resources.

What we have found in the United States at the end of the 20th century, though, is basically a return to Edison's model—with successful research organizations, public or private, developing a highly productive mix of internal and external projects. There appear to be an increasing number of private sector research laboratories that combine their own internal projects—often funded with federal money—with contracted research for other firms. Some of their innovations show up as a winners of R&D 100 Awards.

CONCLUSION

These findings suggest that the U.S. federal government's role in fostering innovation—both in terms of organizational auspices and funding—across the U.S. economy has significantly expanded in the last several decades. But the federal government's role is not to act as the agent of centrally planned technological change.

In Chalmers Johnson's classic account of the Japanese model of industrial policy, he shows how government officials, working at the Ministry of Trade and Industry, operated as both coordinators and financiers for the conquest by Japanese firms of new markets.[39] Japanese government officials were implementing a shared plan that linked investments in particular technologies with specific business strategies to win in particular markets—both domestically and internationally. That strategy may have allowed Japan to catch up the leading nations in an array of industries, but it did not and does not fit the new innovation environment where cutting-edge innovation produced in a new collaborative and dispersed models is the key to success. It is for that reason that many other nations have shifted their innovation policies to be less directed.

In the United States, there is no central plan for innovation, and different federal agencies engage in support for new technologies often in direct competition with other agencies. The federal government has created a decentralized network of publicly funded laboratories where technologists will have incentives to work with private firms and find ways to turn their discoveries into commercial products. Moreover, an alphabet soup of different federal programs provides agencies with opportunities to help fund some of these more compelling technological possibilities, just as there has been increasing support, at both the federal and state levels, for industry-university research collaboration.[40]

Complementing these decentralized efforts are more targeted federal government programs that are designed to accelerate progress across specific technological barriers. Today, for example, the Advanced Research Projects Agency in the Department of Defense is prioritizing support for computer scientists to find ways to overcome the obstacles to creating ever more powerful microchips for computers. It is also helping biological scientists find ways to accelerate the production of large batches of vaccine, which would be useful to protect the population both against biological weapons and a global pandemic of a deadly influenza. For these targeted efforts, officials in these government offices decide to renew grant support to one research group because it has made progress, withhold it from another research group that appears to be heading towards a dead end, and encourage connections with still another research group—working on a seemingly unrelated problem—because they suspect that the third group's findings might have relevance for solving the targeted problem.

Both types of U.S. government innovation initiatives—decentralized and targeted—are increasingly described with the language of venture capital. Private sector venture capitalists, such as the famous firms in Silicon Valley, have an open door policy for scientists and engineers who have a bright idea for a new business. Of every hundred pitches they hear, they might decide to invest in 20 with the idea that if even one or two of the 20 are successful, then they make vast amounts of money that they can recycle into new rounds of initial investments. But the key assumption behind venture capital is that even after careful screening, most of these new business ventures will fail. Some won't be able to develop the promised technology, some won't find a market for their particular innovation, and some won't be able to build an organization capable of exploiting the market. Nevertheless, the enormous gains from the small percentage of winners are more than enough to cover the losses from the others.

Many U.S. government officials now use the same rhetoric. They know that most new startups begun by scientists and engineers at universities or government laboratories will fail, but the minority that succeed will create jobs and advance new technologies. With the decentralized approach, they may provide support to several hundred firms with the idea that 20 to 50 might actually flourish. With the more targeted efforts, they realize that in each funding cycle, only a minority of the researchers will make any significant headway on the key problems. But the idea is that over time, a few incremental advances will eventually set the stage for the big breakthrough that they are looking for.

The largest federal government program that fits this venture capital model is the Small Business Innovation Research (SBIR) program. In 2004, the SBIR program gave out more than $2 billion for some 6,300 separate research projects. The success of programs such as SBIR helps to explain what is perhaps the most surprising turn in federal innovation policy of the last decade.

Starting with the Central Intelligence Agency (CIA) in 1999, a number of government agencies have now set up their own venture capital operations. The CIA's venture capital arm, In-Q-Tel, maintains its own Website and lists 90 recent startup firms in which it has invested. Congress provided a $500 million initial fund, and just as with private sector venture capital, the idea is that the initial fund will be replenished and expanded as In-Q-Tel sells its stake in those firms that have been successful. The Department of the Army has followed the CIA model, and the Department of Energy has partnered with Battelle—the large nonprofit organization that manages several of the department's labs—which has now created its own not-for-profit venture capital arm with an emphasis on supporting startup firms that originated in the laboratories.

Although this explicit turn towards venture capital by U.S. government agencies is understandable, it will not, by itself, solve what we see as the main weaknesses in the current system of federal support for innovation in the United States. In our view, the system of federal support for innovation has enormous strengths, but it also suffers from three major, interconnected weaknesses. First, the system carries decentralization to an unproductive extreme. Under current arrangements, it is entirely possible that five different government agencies might be supporting 30 different teams of technologists working on an identical problem without a full awareness of the duplication of efforts. This situation is a particular problem if different groups are unable to learn from each other in a timely fashion. Second, because the importance of the federal role in fostering innovation is not widely recognized, federal programs in support of innovation lack the broad public support that would be commensurate with their economic importance. Third, the budgetary support for the current system is inadequate and uncertain. Funding for more collaborative research and commercialization efforts are relatively limited, and total federal levels of R&D spending have been declining in real terms since 2003. These declines put the entire U.S. innovation system at risk.

This analysis has shown a dramatic shift in the locus of innovation in the U.S. economy that has occurred over the last three decades. We hope these findings spur a broad debate about the changing role of the federal government in our national innovation system.

ENDNOTES

1. This research was made possible by a grant from the Ford Foundation and support from the University of California Washington Center. We are deeply grateful to Jason Logan and Chris Knight for research assistance.

2. Glenn R. Fong, "Breaking New Ground or Breaking the Rules: Strategic Reorientation in U.S. Industrial Policy," *International Security* 25(2):152-186, August 2000; and Henry Etzkowitz, "Innovation in Innovation: The Triple Helix of University-Industry-Government Relations," *Social Science Information* 42 (2003):293-337.

3. Gregory Tassey, *The Technology Imperative* (Cheltenham, U.K. and Northampton, Mass.: Edward Elgar, 2007).

4. Tassey, *The Technology Imperative,* 2007.

5. Studies that point to a U.S. advantage in collaboration include Steven Collins, *The Race to Commercialize Biotechnology: Molecules, Markets and the State in the United States and Japan* (New York: RoutledgeCurzon, 2004); and Rebecca Henderson, Luigi Orsenigo and Gary P. Pisano, "The Pharmaceutical Industry and the Revolution in Molecular Biology," in David C. Mowery and Richard Nelson, eds., *Sources of Industrial Leadership: Studies of Seven Industries.* (Cambridge: Cambridge University Press, 1999): 267-311.

6. Daniel Bell, *The Coming of Post-Industrial Society* (New York: Basic Books, 1973); and Howard Brick, *Transcending Capitalism: Visions of a New Society in Modern American Thought* (Ithaca: Cornell University Press, 2006).

7. Donald Stokes, *Pasteur's Quadrant: Basic Science and Technological Innovation* (Washington: Brookings, 1997).

8. Michael E. Porter, "Capital Choices: Changing the Way America Invests in Industry," *Journal of Applied Corporate Finance* 5, no. 2 (Summer 1992):4-16.

9. Bennett Harrison, *Lean and Mean* (New York: Basic Books, 1994).

10. Robert D. Atkinson, "The Globalization of R&D and Innovation: How Do Companies Choose Where to Build R&D Facilities?" Testimony to House Science Committee, October 04, 2007, available at <www.itif.org/index.php?id=102>; and Richard Rosenbloom and William J. Spencer, eds., *Engines of Innovation: U.S. Industrial Research at the End of an Era* (Boston: Harvard Business School Press, 1996).

11. Tassey, *The Technology Imperative*, 2007.

12. John Alic, *Trillions for Military Technology* (New York: Palgrave, 2007).

13. Fong, "Breaking New Ground," 2000.

14. Precompetitive research is defined as everything before the development of a saleable prototype.

15. Congress transformed the Advanced Technology Program into the Technology Innovation Program in 2007.

16. E. Raymond Corey, *Technology Fountainheads: The Management Challenge of R&D Consortia.* Boston: Harvard Business School Press, 1997; and Andrew P. Cortell, *Mediating Globalization: Domestic Institutions and Industrial Policies in the United States and Britain (*Albany, NY: SUNY Press, 2006).

17. Etzkowitz, "Innovation in Innovation," 2003; and Fred Block, "Swimming Against the Current: The Rise of a Hidden Developmental State in the United States," *Politics & Society* 36:2 (June 2008): 169-206.

18. The procedures used to nominate and evaluate innovations for the *R&D 100 Awards* and the award winners are described on *R&D Magazine*'s Website at <www.rdmag.com/100win.html>.

19. For example, studies of Nobel-prize winning scientists or of highly cited scientific articles use an opportunistic sample that reflects the evaluations of a particular group of experts.   While members of the sample are definitely not typical, analyzing them can teach us about the best forms of scientific practice. In the same way, our sample instructs us about innovative practice at its best.

20. In those cases where a public laboratory or a university is listed as the sole developer of a product, it generally means that they have licensed the technology to a private firm that has made the innovation commercially available.

21. David Roessner et al., *The Role of NSF Support of Engineering in Enabling Technological Innovation* (Stanford: SRI Policy Division, 1997).

22. In a small number of cases, we added collaborators who were not credited in the magazine but were mentioned in other sources.

23. The focus in this paper is on financial support, but in-kind government support is an increasingly important factor in technology policy. In 2006, the U.S. Department of Energy, which runs many of the big government laboratories in the United States, reported that there had been 2,416 active arrangements where Department of Energy labs did work for others with some partial compensation and 3,474 user agreements where firms were allowed to use laboratory equipment.

24. Even this new database neglects in-kind assistance such as extensive consultations and experiments run at a federal laboratory.

25. The Fortune 500 list was reconfigured in 1995 to include financial firms and retail firms that had not been previously included. We think this shift has had little impact on our results because most of the big firms that had been winners in the 1970s ands 1980s were among the 100 largest firms.

26. In the case of collaborations, we have chosen to attribute them to a single organization to avoid double counting. If a university is a participant in a collaboration, the innovation will be attributed to the university regardless of other participants. If no university is present, but a government lab is involved, then the innovation is attributed to the lab. If there is another public or nonprofit participant, the innovation will be attributed to that participant. If all participants are private, then it will be coded in category 3.

27. Fortunately, the percentage of awards going to foreign firms has remained relatively constant, so the growing collaboration among firms across national lines has not yet had a significant impact on this data set.

28. Ann Markusen and Michael Oden, "National Laboratories and Business Incubators and Region Builders," *Journal of Technology Transfer* 21(March 1996): 93-108; and Adam Jaffe et al., "Evidence from Patents and Patent Citations on the Impact of NASA and Other Federal Labs on Commercial Innovation," *Journal of Industrial Economics* 46, 2 (June 1998): 183-205.

29. Jane Fountain and Robert Atkinson, "Innovation as Social Capital," Progressive Policy Institute, Washington, DC, 1998.

30. Andrew Hargadon, *How Breakthroughs Happen: The Surprising Truth About How Corporations Innovate* (Boston: Harvard Business School Press, 2003).

31. Richard Lester and Michael J. Piore, *Innovation: The Missing Dimension* (Cambridge, Mass.: Harvard University Press, 2004).

32. David Hounsheld, "The Evolution of Industrial Research in the United States," in Rosenbloom and Spencer (eds.), *Engines of Innovation* (1996): 13-85.

33. Block, "Swimming Against the Current," June 2008.

34. The logic of using a 1 percent of revenue screen is that it is common among large firms to devote only 3 percent to 4 percent of revenues to R&D expenditures. Thus, federal awards or contracts of that magnitude could help fund a significant increase in R&D effort.

35. There were five additional awards that went to Fortune 500 companies that had contracts to manage government laboratories—two each for Union Carbide and DuPont and one for Monsanto.

36. For more information on state science and technology programs, see the State Science Technology Institute (www.ssti.org).

37. Robert M. Hunt and Leonard I. Nakamura, "The Democratization of U.S. Research and Development after 1980," 2006 Meeting Papers 121, Society for Economic Dynamics, 2006.

38. Andrew Hargadon, *How Breakthroughs Happen: The Surprising Truth About How Companies Innovate* (Cambridge, Mass.: Harvard Business School Press, 2003).

39. Chalmers Johnson, *MITI and the Japanese Miracle* (Stanford, Calif.: Stanford University Press, 1982).

40. The most illuminating discussion of the contrast between the Japanese model and a more decentralized model of government technology policy is Sean O'Riain, *The Politics of High-Tech Growth* (Cambridge, England: Cambridge University Press, 2004).

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