CHAPTER THREE

Federal Support of Research and Development in Science and Engineering

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SUMMARY

Federal funds pay for about a third of all research and development performed in the United States.[1] The effect of these funds is pervasive. As we will discuss, this funding is either based on principle, or politics, or effectiveness. If we consider only the role of government as a funder of research and development, then principles are pretty few and far between. Politically, there is huge support both by politicians and the public. Finally, on effectiveness we will see that it's a checkered history, as one would expect in a game that is played by Washington rules, further complicated by the nature of research and development work: it's like betting on long shots.

This essay discusses the history and effects of years of federal funding in the physical sciences and engineering. In some ways the effect of fed funding on medical and biological sciences is

1. National Science Board, *Science and Engineering Indicators—2000* (Arlington, Va.: National Science Foundation, 2000). *http://www.nsf.gov/sbe/srs/seind00/frames.htm.*

more dramatic, but my background leads me to focus more narrowly, specifically on information technology (IT).

What have the feds funded in IT? Consider this: there is a list of the five hundred most powerful computers in the world.[2] Of the top one hundred, two are owned by private industry to solve problems, the ninety-eight others are owned by government (including non-U.S.) entities or contractors, and the supercomputer vendors themselves. The bulk are in the United States. This is deliberate policy of the National Science Foundation (NSF), Department of Energy (DoE), and the Department of Defense (DoD): to build in the United States the largest infrastructure of supercomputers to keep ahead of our military and economic competitors. Is this a good thing? On the face of it, it sounds like good logic: the computer industry has fueled the recent economic growth in the United States (the Internet, the Web, etc.) and we need to keep priming that pump. If there is a flaw, it is that the supercomputer segment has not grown, in fact most vendors have failed or been acquired in unfavorable circumstances. Control Data, Cray Research, Cray Computer, Thinking Machines, and many others have been eliminated as organizations as mainstream computing environments (based typically on PC technology) take over. Yet the development of the PC was not funded by the feds. In fact, of the technologies that were needed to enable the PC revolution, only one, networking, was created and supported in any serious way by government funding.

Certainly the Internet and Web owe a great deal to government funding. Could this have happened without the government funding? We won't ever know the answer to that, but the fact that proponents regularly point out this one success

2. TOP500 Supercomputer Sites. *http://www.top500.org/.*

story after thirty years of federal funding suggests that the funding has not been as effective as one might hope.

INTRODUCTION AND BACKGROUND

In the United States, federal funds provided for research and development dominate the research and development community. Approximately one-third of all research and development conducted in the United States is paid for by federal taxpayers.[3] The federal government's research and development spending is $62 billion, not counting tax expenditures, out of a total spending of about $200 billion in the United States. Research and development includes a lot—making minor design modifications on a tank or ship design is research and development, but the federal role in more basic research and development is even more dominant. The support for basic research by the feds is between $21 and $29 billion dollars per year (it depends on how you count), an amount that has doubled in the past ten years, and that represents more than half of all of this type of research. In comparison, this third or half is far more than the role of the federal government in the overall economy: federal spending is 18.2 percent of Gross Domestic Product.[4]

Is this dominant federal role appropriate or justifiable? Research and development is not mentioned in the Constitution or any of its amendments and would appear to be a constitutionally unjustified intervention in the economy, yet research and development funding is so deeply embedded in role of the

3. National Science Board, *Science and Engineering Indicators—2000*.
4. *FY2002 Economic Outlook*, Executive Office of the President. *http://w3.access.gpo.gov/usbudget/fy2002/pdf/economic.pdf.*

central government that it is listed by the president in his economic reports as one of the sixteen basic roles of government.[5]

The justifiability of research and development support by the U.S. government can be discussed on principle, or on political realities, or on effectiveness.

POLITICS

Politics can be quickly dispensed with: there is NO political debate on the funding of research and development. The two political parties that dominate U.S. politics compete to see which one can cause the biggest increase in research and development outlays. George W. Bush is raising NIH's budget by a substantial fraction over the proposed Clinton budget. Senate votes on budget for the National Science Foundation can be 95 to 5, or even when bundled with HUD's budget will attract a vote of 87–8.[6] I recall that near the end of his term President Carter nominated a new head of the National Science Foundation, and the Republicans blocked the nomination so that Reagan could nominate the same person and get credit.

Politicians are reacting to public support. In 1999 a survey found that 82 percent of those queried agreed that "even if it brings no immediate benefits, scientific research that advances the frontiers of knowledge is necessary and should be supported by the Federal Government."[7] I can think of no area of government where the expenditures are so great and the controversy so small. Why no controversy? Perhaps because scientists are held in high esteem by the voters. Perhaps because

5. *FY2002 Economic Outlook,* Executive Office of the President.

6. "On Thursday, October 12, 2000 the Senate passed H.R. 4635—the final Senate VA-HUD and Independent Agencies appropriations legislation for FY 2001. The vote was 87–8." From NSF home page *http://www.nsf.gov/.*

7. National Science Board, *Science and Engineering Indicators—2000.*

the funding really has worked—that without it we would all have a much lower standard of living. Perhaps because we as a nation want to win as many Nobel prizes as possible and will spend whatever it takes. Perhaps because we want the highest technology for our armed forces, and realize the amount of research and development that actually takes. Perhaps it's the health research driven by our fears of death and disease.

Clearly, based on the political realities, there is adequate basis for federal funding of research and development.

PRINCIPLE

As to principle, there is no shortage of descriptions of the benefits of government-funded research and development, usually sourced from the government itself, or from agencies supported by government. Government documents and congressional testimony explain why we spend so much money on research and development. It's "necessary to the vitality of the nation" or "contributes to economic growth and productivity." The National Science Board, in its biannual report *Science and Engineering Indicators*,[8] states, "Research and development is a vital and necessary step leading to improved products and services."

The president's *Economic Outlook 2002*[9] says research and development outlays "help the Nation compete in the global economy and improve our quality of life." The president's report goes on: "In the last fifty years, developments in science and technology have generated at least half of the Nation's productivity growth, creating millions of high-skill, high-wage jobs." The basis for adopting this role of government is com-

8. National Science Board, *Science and Engineering Indicators—2000.*
9. *FY2002 Economic Outlook,* Executive Office of the President.

paratively recent. It has to do with the changes the United States caused by World War II.

HOW RESEARCH AND DEVELOPMENT SPENDING WAS FORMALIZED

Prior to World War II, what little research and development funding the U.S. government did addressed specific problems such as agricultural blights, human disease, and calculation of weapon ballistics. Then the world descended into war, and it was a different kind of war, a wizard war. Technical breakthroughs in radar, sonar, magnetically fused depth charges, and code-breaking, to name a few World War II-inspired technologies, had never been used before, yet changed the outcome of the war. The key developments were carried out by "wizards," technically trained people, many of them physicists, who understood these advanced technologies. In the early years of the war England led the development of radar (an acronym for radio detection and ranging) and pioneered electronic code-breaking. In the thirties the United States had been rather far behind in understanding and exploiting science in general. German universities that subscribed to U.S. physics publications arranged to have an entire year's volumes mailed in a single package to save on postage. That meant they would see the articles as much as a year late, but there was no urgency to read U.S. publications because it was so unlikely that any important science would be done in the United States.

By the end of the war this had changed. The War Department had mobilized the best minds in the United States, who were able to take advantage of government money and, unlike the British, were at little risk of being bombed. The Manhattan project (using the physics developed earlier by Europeans) successfully designed, built, and detonated two designs for atomic bombs, bringing the war to an end. The Office of Scientific Research and Development, headed by Vannevar Bush, was formed within the Department of War. Once the end of the war was in sight, FDR formally requested Bush to suggest how to continue the contributions in peacetime. FDR wrote, in part:

> Dear Dr. Bush: The Office of Scientific Research and Development, of which you are the Director, represents a unique experiment of team-work and cooperation in coordinating scientific research and in applying existing scientific knowledge to the solution of the technical problems paramount in war. Its work has been conducted in the utmost secrecy and carried on without public recognition of any kind; but its tangible results can be found in the communiques coming in from the battlefronts all over the world. Some day the full story of its achievements can be told. There is, however, no reason why the lessons to be found in this experiment cannot be profitably employed in times of peace. The information, the techniques, and the research experience developed by the Office of Scientific Research and Development and by the thousands of scientists in the universities and in private industry, should be used in the days of peace ahead for the improvement of the national health, the creation of new enterprises bringing new jobs, and the betterment of the national standard of living.[10]

I'm sure that this letter did not surprise Dr. Bush, who in turn wrote a detailed document entitled "Science—The Endless Frontier" describing how the postwar government scientific enterprise should be constructed. The report proposed the creation of the National Research Foundation, an organization that became the National Science Foundation (not quite right, since the first research issue discussed in the report is

10. Vannevar Bush, *Science—The Endless Frontier: A Report to the President, Director of the Office of Scientific Research and Development* (Washington, D.C.: United States Government Printing Office, June 1945). *http://www1.umn.edu/scitech/Vbush1945.html*.

"the war against disease" which ultimately became the basis for the National Institutes of Health). The report also directly addressed the issue of whether or not the support for science was a proper function of government. On that topic, the report states that "science IS a proper concern of government" and goes on to say:

> It has been basic United States policy that Government should foster the opening of new frontiers. It opened the seas to clipper ships and furnished land for pioneers. Although these frontiers have more or less disappeared, the frontier of science remains. It is in keeping with the American tradition—one which has made the United States great—that new frontiers shall be made accessible for development by all American citizens. Moreover, since health, well-being, and security are proper concerns of Government, scientific progress is, and must be, of vital interest to Government. Without scientific progress the national health would deteriorate; without scientific progress we could not hope for improvement in our standard of living or for an increased number of jobs for our citizens; and without scientific progress we could not have maintained our liberties against tyranny.[11]

The principle on which today we spend $62 billion annually is the opening of new frontiers. I think Lewis and Clark would be amazed.

By the Eisenhower administration, the science-government alliance was in full flower. There was a science adviser to the president. Eisenhower realized that the most powerful weapon in the world, the weapon that had ended World War II, had been designed and built using science so advanced that almost no American had even a small understanding of the physics underlying a fission bomb, much less a fusion bomb. The military was ever more dependent on technology—jets were re-

11. Vannevar Bush, *Science—The Endless Frontier*.

placing propeller planes, radar was critical, the English code-breakers were supplanted by the (now vast and powerful) National Security Agency—and the support of research and development seemed essential. The military became such a force in the United States that Eisenhower, a former army general, said that we needed to be careful of the new military-industrial complex. Since then, Congress and the administration have supported increased research and development budgets. Today, as stated earlier, the federal government spends $62 billion annually to open new frontiers.

EFFECTIVENESS

Whether or not research and development spending is principled or politically necessary, the best practical reason for funding it is that it is more effectively done and used by the state. The remainder of this chapter will discuss this issue.

Is it effective? Recall the sentence, quoted above, from the President's *Economic Outlook 2002*: "In the last fifty years, developments in science and technology have generated at least half of the Nation's productivity growth, creating millions of high-skill, high-wage jobs." Actually the paragraph goes on: "Federal Government support for science and technology has helped put Americans on the Moon, harnessed the atom, tracked weather patterns and earthquake faults, and deciphered the chemistry of life."[12]

What's going on there? It's a pretty carefully worded sentence. Does it say that government support of research and development has helped productivity and created jobs? My guess is that this is what the author hoped you would conclude, but it doesn't actually SAY that. Instead, the author first ob-

12. *FY2002 Economic Outlook,* Executive Office of the President.

serves that developments in science and technology have helped productivity, and that's probably true. But what about federal support? The author says that this allowed us to go to the moon, build nuclear weapons, and so on. But those accomplishments have probably NOT contributed to productivity and high-wage jobs. Thus the paragraph does NOT say that federal support has helped productivity, although most readers would probably conclude the opposite. Unfortunately that's true of a lot of research and development funding: we say it helps the economy or competitiveness or vitality or productivity, but most of it doesn't.

In truth, more than half of research and development spending is done in just two areas: defense and health. Defense is a constitutionally authorized area, and health research has widespread political support because everyone is affected by issues of health and longevity. Perhaps that should end the discussion, but, on the face of it, spending in neither area makes the United States more competitive (except militarily), nor more productive, nor does it improve the standard of living. Since this is the bulk of spending, and we are all wrapped up in our rhetoric about productivity, we argue that defense research and development will provide technology that benefits U.S. industry. In particular, the argument advanced for most research and development is that the work funded by the feds will trickle down into the economy. The only problem with that argument is that there are very few examples where that has happened. As the *Wall Street Journal* stated recently: "Defense industry executives go all the way back to the passenger jetliner to name a military advance that found mainstream popularity."[13]

To discuss the question of effectiveness in more detail, this

13. *Wall Street Journal*, April 25, 2001, A1.

chapter now explores the role of federal funding in just one area: information technology. Computers are important to the economy, and federal research and development money was used, so it's a good case. In fact, it's the one most likely to be rolled out in defense of federal involvement in research and development. And it is also the area with which I have the most personal familiarity, as I am a computer scientist.

SOMETHING ABOUT ME

Before discussing the involvement of the U.S. funding of computers and networking, let me provide some personal background. My education and employment in the computer industry cover the period 1960 to 2001. I have an undergraduate engineering degree from Harvey Mudd College, an electrical engineering master's degree from Caltech, and a Ph.D. from the University of California at Berkeley. My Ph.D. is in electrical engineering and computer science (EECS). That name reflects not only my history, but the history of many of the folks who jumped on the computer bandwagon in the sixties and seventies. When I enrolled at Berkeley in the 1960s, I joined the Electrical Engineering Department; however, it was clear to everyone that the important application of many of the principles of electrical engineering would be found in digital computers. (Just for the record, there were analog computers—the term digital computer is not redundant.) Thus I and many of my colleagues became involved with computers, and the name of the department itself had changed by the time I completed my degree.

By the time I was ready to get a job after receiving a Ph.D., I had worked at six organizations in technical positions: a Navy laboratory, System Development Corporation (a spin-off of Rand Corporation to run missile defense and air traffic control), Hewlett-Packard, Bissett Berman (a company with a prime NASA contract to do navigation on the Apollo moon missions), Stanford Research Institute (now called SRI), and University of California, Berkeley. All but one of these organizations was carrying out research and development using federal funds and under federal contract.

My work has always had to do with computers, from relatively early computers from the late fifties to modern machines. Let's look at the role of the feds in the development of the computer industry.

EARLY HISTORY OF COMPUTERS

Computers were developed to calculate answers to numeric problems. (This is distinct from punched-card equipment, mostly made by IBM, that was used by the census and by insurance companies.) Early adopters of computers had numeric questions: where was Jupiter going to be next week? This led IBM to support astronomers at Columbia in the 1940s. More commonly, computers were needed to figure out where a shell fired from a battleship was going to land. This application drove most of the early computer designs, mostly paid for with Department of War money. A few brilliant scientists and engineers realized that a computer could compute more than just numbers, and developed computers that could, for example, break German codes. The ballistics and code-breaking applications were peculiar to defense needs, and thus the early support for these computers came from the defense establishment. As Encarta states, "At first, only the government used computers." There are few examples of early government support leading to such an important and broad-sweeping industry.

HOW COMPUTERS EVOLVED

Soon after computers were developed by universities and government labs, private companies jumped into the business. The most famous of these was Univac, a name that was almost synonymous with computers. (The Univac name and business were later purchased by Remington Rand.) These were companies that focused on the applications the government wanted and received substantial federal support for their research and development to develop products. In 1951, to pick a date when the outcome was quite in doubt, it appeared that the "giant brains" would be used only by the government, working on very large problems, because the machines were so expensive and massive that only a project like the census or the military could use them. Computers were certainly thought of as a new thing but no one predicted what would come next.

What came next was a rapid conversion of the electronic data processing business from punched cards to computers that in turn used punched cards. It turned out that expertise in punched cards (originally developed by Herman Hollerith to help the census of 1890) was vital to success in the computer business, and as IBM fortunes rose, the fortunes of Univac and the other computer companies declined. While it's probably an exaggeration to say this, Univac declined while focusing on the special needs of government and IBM thrived by satisfying business needs.

BACK TO ME: CHOOSING AN EMPLOYER

By the sixties, the role of federal funding in the evolution of computers had declined, but they were still the dominant supplier of research funding in computer science. Going back to my personal experience, by 1969 I had worked at six companies, and five of them were doing computer research funded by the feds. The one exception was Hewlett-Packard, where I and others in the laboratory were designing instruments like signal generators and oscilloscopes using HP's internally generated funds. As a practical matter, someone with my training was most likely to wind up working for a government contractor or a university, but also for organizations like SRI.

My experience with contractors caused me to try to avoid federal contracts. There were just too many problems associated with federal funding: chasing the contract itself was a huge but largely nontechnical project that consumed lots of time and energy, and it was anticlimactic when the contract was acquired. The scope of work seemed to be controlled by bureaucrats located far from the lab. The focus was too much on defense and space, areas that seemed to me to have little hope of ever seeing application in the real economy. Even if the project did not appear to be a defense project, it always had to be justified as important to the Army or whatever. A funding agency might say, "We need natural language understanding by computers so that the captain can control the ship." While today there are many privately funded jobs available in the IT (Information Technology) industry for skilled engineers and computer scientists, that was not true thirty years ago. Even today, most researchers who are interested in fundamental problems in computing work in the major universities that are large federal contractors. Sixty percent of all research and development conducted by universities is paid for by the feds.[14]

I decided that I didn't like the life of a government contractor, but in 1969 if you didn't want to work for the government,

14. National Science Board, *Science and Engineering Indicators—2000.*

where did you go? I joined IBM, which had a research laboratory in Yorktown Heights, New York, that was generously funded from internally generated funds. At the time there was only one other lab like it—Bell Labs in Murray Hill, New Jersey, funded from internal AT&T funds. As it turned out, the decision to avoid government contracts was wonderful—it led to a long and satisfying IBM career. It's a wonderful illustration of being able to act on my view that government's role in the economy should be minimal. At least I could take myself out of direct dependence on government funding.

SIGNIFICANCE OF INFORMATION TECHNOLOGIES

There is little question of the importance of the computer industry in the economic life of our nation and the world. *Science and Engineering Indicators—2000* starts chapter 9 with the statement that IT industry growth is responsible for 29 percent of growth in national income in 1998, and declining prices of IT equipment reduced inflation.[15] While the chapter does not claim a connection between research and development funding and the importance of the IT industry, the general theme of the document certainly implies it.

Where is the government spending money now? Where did it NOT invest? Let's look first at an area that has received special treatment from the government, and a large amount of funding: supercomputers.

15. Ibid.

SUPERCOMPUTERS

Government has been supporting the construction of the biggest computers since the beginning of computing. I guess it's like bombs and airplanes, if we can build a bigger or faster one, let's do it.[16] Even today, the federal government pays for the largest computers. Of the largest and most expensive computers in the world, all are owned by government labs with only one exception: a machine at Charles Schwab.[17] How is it that government owns the most expensive computers in the world? They don't own the best cars, the best tractors, the best steel mills, the best stereos; what is it that has them own the best computers? To answer this we can look at the uses to which these machines are being put: all but a few of the top twenty machines are applied to weather prediction, nuclear weapon design, code-breaking, and high-energy physics. Let's consider these four applications.

Weather? It is a hard problem, is helped by faster computers, and is the more or less exclusive realm of the government because they give away the information. The price they ask makes it difficult for a competing private institution. Code-breaking and signals analysis? Again, only the government imagines that there is that much value in listening to the electronic signals of economic competitors and rogue nations. High-energy physics? Again, no economic value—this is really

16. Spring Joint Computer Conference, *AFIPS Proceedings* 36 (1970): 543–49.

17. The Top500 organization cannot track ALL computers. It tracks the ones it knows about. There is probably a bias in their choice of computers—the ones listed by them tend to be computers used in scientific computation. For example, Google (*www.google.com*) or Yahoo (*www.yahoo.com*) may own computers that in the aggregate are large enough to qualify for Top500 status, but they are not listed. *http://www.top500.org.*

research, and the prestige of the nation is thought to be on the line. We get a disproportionate number of Nobel prizes in physics, and we want to keep getting them. Nuclear weapons? No one wants them except governments. To test this, let's look at the list of the top one hundred machines. Ninety-four are owned by government labs, government-funded centers, or by the vendors themselves for testing. Six are owned by industry.

Each of these multimillion-dollar supercomputers is applied to a problem that only a government would care about, but why do they use supercomputers? The U.S. Congress has little problem justifying the billions spent each year on acquiring and operating these machines, and yet private industry spends almost nothing on these monster machines. That's because they are much too expensive for the return. Here government has a Manhattan-project attitude: if there's a way to spend more money to do a better job, then spend it. In contrast, commercial enterprise looks not at effectiveness, but at cost effectiveness. For most problems (the Charles Schwab machine being a possible exception) supercomputers are not the best solution.

What is the best solution? The personal computer. There must be some good reason why there are millions sold each year, in fact, for the vast majority of IT issues, personal computers and the servers (mostly based on the same technology as the PC itself) that support them are the technology of choice, so what did the government have to do with the productivity-enhancing IT systems that we all use today? The key inventions that led to the small high-performance systems that we have today can be placed in seven categories. I have listed one or two of the companies that are influential in this market.

overall design	IBM, Apple
applications	Microsoft

middleware (e.g., database)	Oracle, Microsoft
system software	Microsoft
networking	Cisco, 3Com
storage (e.g., disk drives)	IBM, Seagate
microprocessors and DRAM	Intel

What was the role of government funding in this? We will explore each in turn, but the bottom line is that one area, networking, of these seven areas has been led by fed-funded research and development. In the other six areas, the federal funding has not been a crucial enabler.

SYSTEM ARCHITECTURE

The stories of the invention of the Apple PC and the IBM PC have been described in many places. Suffice it to say that government money played no role in either design effort.

APPLICATIONS

Whether we consider personal productivity applications like Microsoft's spreadsheet and word processing or if we look at SAP's enterprise applications, there has been no significant government funding involved.

MIDDLEWARE

For the most part, federal funding played little role in the development of companies like SAS Institute, Oracle, and others. Yes, the very first version of Oracle's system was developed for the CIA under contract, and yes, some key pieces of middleware associated with networking (in particular the web browser that led directly to Netscape) were funded by the feds, but beyond this there are few examples of federal funding of research and development that contributed to today's U.S. dominance of middleware.

SYSTEM SOFTWARE

The federal funding of software has played a small but important role in the evolution of software. One example: engineers at AT&T Bell Labs using AT&T's money had developed as a research project an operating system called Unix. Because AT&T was prevented by law from entering the computer business, it did not sell Unix directly but instead licensed various nonprofit organizations to use it. It was the original open source product, at least in the sense that the organizations that licensed it received source as well as object.

The Department of Defense funded the support and enhancement of the original Unix in an effort to rationalize the computing environments used by the many Department of Defense research contractors. This effort was known as Berkeley Unix, or BSD (Berkeley software distribution). This has certainly been effective in laying the groundwork for several important developments. Sun Microsystems was founded as a Unix workstation company, using BSD and in fact hiring the key programmers from the University of California, Berkeley. The whole Open Systems movement revolves around Unix; the Gnu software complex that includes the Gnu compilers again revolves around Unix. In fact, Gnu itself is an interesting self-referential acronym—Gnu stands for "Gnu is Not Unix." However, Unix was not able to develop into the foundation of most computing. That role was taken by Microsoft. Originally Microsoft took their operating system inspiration from CPM but later was influenced by Unix. Of course Unix itself was influenced by work that preceded it.

Net: while U.S. spending on system software had some impact, the major impact of Microsoft's system software did not depend in any important way on previous federal support of system software research.

NETWORKING

In this area there has been a major contribution by research and development funded by the government. This is worth a whole section of this article.

STORAGE

The key development in this whole area is the disk drive originally developed by IBM using internal funds. IBM's ideas were later exploited by Seagate, who pushed the technology into smaller packages. The feds have supported research institutions at Carnegie-Mellon University and others on pushing the envelope of magnetic recording, but this has not been critical to the amazing advances of magnetic recording being made by the privately funded disk-drive industry.

Department of Defense did support a small research project at Berkeley that led to RAID (reliable array of inexpensive disks), and the RAID work has been critical to the evolution of storage systems.

DRAM

Originally modern DRAM (dynamic random access memory) was invented by and developed for industry. An engineer at IBM invented the concept of DRAM, and IBM first introduced DRAM (also known as solid-state memory) in its computers to be used, as usual, for a company that called itself a business machine company, for customers like insurance companies. Later, again in the late 80s, the feds played a role in DRAM. It's the same story as the role in silicon: the United States was concerned that all DRAM manufacturing would move to Asia. Since DRAM is a key technology, the United States offered what amounted to subsidies to companies manufacturing DRAM in the United States. Today most DRAM is manufactured offshore, and most of those companies do not make much money doing it.

MICROPROCESSORS

The evolution of microprocessors, from the early Intel chips that were embedded in Japanese calculators to the latest Pentium IV, was driven primarily by industrial requirements. The government did not play a major role. This story is not dissimilar to the technology story: for the most part the Department of Energy and the Department of Defense thought they wanted the highest possible performance. They were led thus to supercomputers, and microprocessors were perceived to be too weak to satisfy serious computing needs. NASA needed compact machines for onboard computing, but man was already back from the moon before the microprocessor was developed.

The primary conclusion to be drawn from this summary of the key technology underlying modern computing is that the feds support of information technology research and development did not play a decisive role in forming the industry, with one notable exception: the Internet. It is therefore necessary to look into this story.

THE FEDERAL ROLE IN CREATING THE INTERNET, THE WEB, AND ALL THE NEW NEW THINGS

I recall clearly the day I went to my student office at Berkeley and observed a big moving van parked in front of the building. A new project, the ARPANET, funded by the Advanced Research Projects Agency of the Department of Defense, had recruited one of the faculty stars from Berkeley, and the van was moving his office contents back East. That piqued my interest, and I carefully read all the documents that were produced over the next ten years. The first paper I read was by Larry Roberts on the architecture and motivation for the network. The title provided the primary justification: "resource sharing."[18] This was an interesting idea. In the sixties and seventies, every research and development center—mostly universities—wanted a big computer. ARPA's funds would be quickly depleted if every contractor was provided with the biggest computer available. Recall that these computers could cover more than ten thousand square feet, requiring enough air-conditioning to run a city. They cost millions and were a big prestige symbol. When IBM built a new research lab in San Jose, California, the design concept was a large machine room with many offices overlooking it from above; as though the best view California offered was that of a big computer. The idea behind the ARPANET was to offer to every ARPA contractor access to all the big computers, independent of geography. That way researchers in Wisconsin could get access to the big IBM computer at UCLA, and ARPA wouldn't have to buy one for Wisconsin, or so they hoped. It didn't really work

18. Lawrence Roberts and Barry Wessler, "Computer Network Development to Achieve Resource Sharing."

out that way. Instead, the ARPANET became the Internet, and certainly became the most important development in information technology. Not only did the ARPANET lead to the Internet, but it also drove competing designs away. While this might be considered a bad thing—"What were the feds doing funding stuff that had the effect of destroying all that privately funded work on networking"—in fact, it was the right thing technically. I saw this from the IBM perspective.

ARPA had encouraged (and sometimes required) widespread distribution of the information on the network design. The protocols, the packet design, and the software were all widely examined and understood. In contrast, IBM's networking architecture was different not only in detail, but in the openness of the design. IBM's computer networking was called System Network Architecture (SNA) and was a proprietary session-oriented approach that was very different from the ARPANET direction. Further, IBM and certain other major research and development centers were isolated from the ARPANET itself because the feds did not charge for the use of ARPANET and therefore you had to be a major ARPA contractor to get access to the network. I recall a meeting on this in the mid-seventies. IBM had hired some professors from MIT who were intimately familiar with the ARPANET to come and provide advice on the evolution of SNA. The MIT professors wrote a report that said, in effect, "we don't really understand what IBM is doing so we can't really help you." Whoa! The consultants said that IBM should spend more time thinking about the protocols used in the ARPANET. As it turned out, they were right and SNA slowly died.

The ARPANET/Internet/Web is a wonderful development—like the personal computer it has become ubiquitous—and has scaled a degree never imagined by its designers and developers. There is no question that the federal funding of the initial ARPANET was responsible in a major way for the success of this major innovation. We can't know how it would have turned out without the ARPA money; but we do know that the Internet today is a direct descendant of the work done in the late sixties by a bunch of very talented computer scientists working under the leadership of a couple of guys in the Department of Defense. Without question, this is an accomplishment. But even in a success story we can see the pitfalls of government funding of research and development.

A MAJOR PITFALL: SATISFYING THE FEDERAL RESEARCH AND DEVELOPMENT CUSTOMER

Effectiveness is a key metric of judging federal research and development funding, absent a sound principle on which to base the spending. The experience of World War II led directly to the major involvement of the government in research and development. The feds have supported many areas of computer research and development, and regularly draw attention to the huge success of the Internet. Other success stories are fewer and farther between. Recall the list of companies involved in the early evolution of the modern computing environment? To repeat:

overall design	IBM, Apple
applications	Microsoft
middleware (e.g., database)	Oracle, Microsoft
system software	Microsoft
networking	Cisco, 3Com
storage (e.g., disk drives)	IBM, Seagate
microprocessors and DRAM	Intel

Which one of these received major fed funding? None, I believe. Where's Bolt Beranek and Newman, a major contractor on the ARPANET? Where are the NASA and Department of Defense contractors who received vast sums to develop computing environments? You rarely hear about the contributions of General Dynamics or Lockheed to modern computing. My guess is that the companies that depended on federal funding looked to satisfy the customer (as they should) and that meant satisfying the funding agencies. It's a rare case when satisfying a funding agency leads to commercial success in the competitive world marketplace.

Consider the companies below, some of which got lots of research and development money from the government, and others got comparatively little. Which have done better over the years?

- Didn't get money: Apple, Cisco, Intel, Microsoft, IBM
- Got lots of money: North American Aviation, General Dynamics, Bolt Beranek and Newman, Lockheed Martin, Computer Science Corporation

A MAJOR PITFALL: LACK OF DIVERSITY

Think of Adam Smith's invisible hand. It picks winners based on marketplace competition. How does that work in fed funding? Well, there's only one federal funder of research and development. No invisible hand is going to come around and knock off that funder and replace it with another. Thus we have a monopoly regulated only by the processes of fed funding. Those processes include getting good people to propose project areas and oversee the review processes, peer review and competitive bidding, along with the usual pork-barrel rules.

There is no question that NSF and ARPA get good people to spend a portion of their careers helping to manage the research and development spending. They are certainly well-intentioned, but face no test of market effectiveness. Peer review tends to ensure the scientific worthiness of a proposal, and is effective in weeding out technically worthless ideas. It does not, however, help to FIND ideas. In fact, there is a large "piling-on" effect in fed funding of research and development. The project manager decides that a certain area should be funded. For example, at one point the feds made it clear that they wanted to fund research and development in software engineering tools and object oriented programming, and the proposals poured in. The ideas followed the dollars, not the other way around.

Following the fashion is also a defect of privately funded research and development, but not nearly as serious. Much more diversity arises in privately funded research and development. Of course the federal funding agencies try to find out how effective they are by counting papers published, or encouraging industrial matching money (but this is hard—see below), or by looking for commercial applications of fed-funded research and development, but it is fundamentally impossible to support the kind of research and development diversity that arises in a free market.

Mixing federal and private money to fund a specific research and development project has always been difficult. Initially places like NSF did not want any confusion about how their money was being used, and insisted that any results from the research and development paid for by NSF be placed in the public domain. In the past ten years the funding agencies have softened this stance and are trying to encourage joint funding, but it is still difficult. Basically the fed funding agencies are very sensitive to the criticism that they are giving public monies away to private companies. It's pretty much OK to give public monies to colleges and government agencies, but not private companies, so they try to get agreement that the results will be openly published and that any patents will be made available to others. This conflicts with the needs of private industry, which usually spends the research and development money to gain a competitive advantage.

A MAJOR PITFALL: FUNDING IS A MONOPOLY

Since sports metaphors appeal to some readers, imagine the following variant on baseball. You are given the bat. You stand at the plate, and try to hit the ball. You can swing as often as you want since there are no strikes and no balls, and you can just wait for your pitch and try to hit it. There is no penalty for swings, or fouls, or hitting poorly. After some long period of time, we count up the good hits and say, "Amazing, you hit forty-seven singles and fifteen doubles. Great!" When there's only one hitter, and no limit to your swings, you are BOUND to get hits. Thus it is with research and development funding. Eventually something will work out. Then, like the Internet, it is touted as a major accomplishment (which it is, after all). But is this the way to play the game?

Like our imaginary batter, there is ultimately one organization responsible for this government support of research and development, the government itself. It decides, and given the lack of public debate, the staffs who run the funding agencies decide, who wins and loses. The marketplace of ideas, science, and progress itself, is controlled by bureaucrats, however competent, in Washington.

CONCLUSION

We lack a guiding principle for federal funding of research and development. Because there is so much public support and political support for research and development spending, the public debate that normally deals with political decisions is largely missing, so we are left with the argument that it works. We've seen that it can work. The feds funded the key work that led to the Internet and Web (a good thing) and has led to the dominance of government-owned supercomputers (a bad thing?).

The U.S. government has spent a few hundred billion dollars of taxpayers' money on research and development in the past two decades. The politicians are happy, citizens like it, and staffs at NSF, ARPA, and similar funding agencies are competent. The funding has produced some home runs like the Internet. We'll always have a need for a certain level of government-funded research and development given our desire to have the most powerful army in the world. Maybe there's no issue.

But there are issues because there is no principle to justify or defend the spending. "Vitality of the nation" is simply not sufficient. That's the way you justify supporting the symphony or ballet, not $62 billion in spending each year. There is no substantive political debate. Finally, in spite of many efforts to track it, there is really no way to establish that the money is effectively spent. It is neither enough to count Nobel prizes (that's the first table in Science and Engineering Indicators) nor it is sufficient to cite the success of the Internet, however great that accomplishment is.

We've described three pitfalls in the funding system:

- There is a virtual monopoly on running the funding system.
- The monopoly creates a lack of diversity in ideas.
- The folks who play the grant-contractor game the best are often least likely to succeed in the commercial marketplace.

If we could create a national debate on these issues, and on a set of related issues that surround government funding of research and development, that would be a good start.