THE ROLE OF GOVERNMENT IN ENERGY TECHNOLOGY INNOVATION: INSIGHTS FOR GOVERNMENT POLICY IN THE ENERGY SECTOR

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SPONSORING RESEARCH PROGRAM

The Energy Technology Innovation Project (ETIP) at the Belfer Center for Science and International Affairs is a joint project of the Science and Technology Policy Program and the Energy and Natural Resources Program. Our focus is on crafting and catalyzing a set of policies and institutions that can stimulate the research, development, and deployment of energy technologies that can address the full range energy-related challenges of the 21st century, including environment, development and security issues. ETIP has ongoing research in two areas: (1) Energy Technology Policy for a Greenhouse-Gas Constrained World and (2) Technology Innovation Studies. In the first area, we are currently focused on the U.S., China, and India, with a strong emphasis on the role of international cooperation in the development and deployment of cleaner energy systems. In the second area, we examine how government policy and programs can play an effective role in stimulating private sector investments in the development and deployment of cleaner energy technologies.

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THE ROLE OF GOVERNMENT IN TECHNOLOGY INNOVATION: INSIGHTS FOR GOVERNMENT POLICY IN THE ENERGY SECTOR

Executive Summary

This volume presents insights for the design of government policy to promote technology innovation in the energy sector. These insights are based on a comparative analysis of the history of government involvement in four sectors (computers and electronics, agricultural biotechnology, industrial chemicals and the power sector) as well as an analysis of government's historic role in defense and civilian technology innovation. In this executive summary, overall findings for each topic are presented first, followed by specific lessons for the energy sector.

Multiple Policies: Simultaneous Government Support for Supply-Push and Demand-Pull Policies

Multiple policies, working together in a synergistic package, were the key to successful technological innovation and particularly to the success of radical technological transformations in computers/electronics, agricultural biotechnology, and power sector technologies. This included policies that increased R&D (supply-push policies) as well as policies that supported the development of markets for emerging technologies (demand-pull policies).

- Multiple policies throughout the innovation process will be needed to support on-going technological innovation in the energy sector. The need for simultaneous supply-push and demand-pull policies is supported by the histories examined in this volume, as well as because of market failures throughout the innovation process in the energy sector. These market failures result in under-investment by the private sector in research, development and deployment of new energy technologies.

Supply-Push Policies

<u>Long-term support for both basic and applied R&D</u>

Government support for basic scientific R&D laid the groundwork for successful innovation in all of these sectors by developing the knowledge necessary for technological inventions and training the scientific workforce. For three of the sectors – computers and electronics, agricultural biotechnology, and power sector technologies – multi-decadal governmental investments in both basic and applied scientific and technological R&D were also critical to successful innovation

- On-going investments in basic R&D as well as applied R&D focused on reducing costs and improving quality is needed to support innovation in the energy sector.
- Even after first commercialization, government support for continued radical component and process innovations may be needed for energy technologies that are largely valued for their public good qualities (e.g. ability to reduce pollution or increase energy security).

Public-Private Partnerships

Public-private partnerships are a proven approach for successful technological innovation. Guidance for the use of public-private partnerships includes:

- Set "stretch" goals, i.e. goals that are beyond what firms would do on their own, but reachable within the timeframe of the project.
- Use public-private collaboration for goal setting as well as implementation. Engage additional relevant stakeholders in the goal-setting process.
- Make provisions for the involvement of universities (see below).

R&D in Universities

The productive relationships between universities and industry are one of the factors underlying the successful innovation in these cases. Universities serve as a laboratory for more risky research, a launching pad for innovative high-tech companies, and a training ground for the next generation of entrepreneurs and technically skilled workers.

Portfolios and Performance Measurement

The government's applied R&D portfolio should be weighted toward riskier investments, i.e. investments that are too risky for firms to undertake alone, because of technological and/or market uncertainties.

- Program success should be measured at the portfolio level, and not at the level of individual projects. Failure of individual projects must be expected; excess success means that the government has not invested enough in high-risk technologies.
- Technological success, even without market penetration, should be valued if it provides options for addressing potential future problems.

Demand-Pull Policies: Creating Markets for Technological Innovations

Demand-pull policies played a role in all of the sectors, but were more prominent in some sectors than in others and the specific instruments varied considerably. Sectoral differences that account for this include: relation to priority national missions such as defense, economic competitiveness, and environmental protection; the need for specific types of complementary and enabling infrastructures; and market characteristics.

Niche Market Creation

Early markets, also known as niche markets, are an important route for successful commercialization of new technologies. Government played varying roles in the creation of markets in these four cases, sometimes being limited to regulatory policies that structured the market, and in other cases also creating markets through procurement and tax incentives. Four key lessons regarding market creation policies emerge from comparisons across these cases.

- In cases where there is a private market willing to pay more for the qualities provided by the new good, government will often need to structure regulations and standards, but not provide direct support for niche markets.
- When there is not a private niche for the initial use of the good *and* if there is a strong public interest in pushing the good through commercialization, then government will need to play an active role in creating initial markets for the demonstration and deployment of the technology. This initial market can put in motion the process of technological learning that may eventually make a technology cost-competitive.
- Government support for initial markets is even more crucial and may need to be of longer duration if the product in question is a commodity good.
- Government support for niche markets can also support the public goal of economic growth and competitiveness, as early and/or large-scale deployment can create competitive advantages for firms and nations.

Complementary and Enabling Infrastructure

Many new technologies require new physical and/or institutional infrastructures to be attractive in the private market. In instances where market failures or collective action problems prevent the private sector from creating such infrastructures, government may be able to play an effective role.

- In cases where shared physical infrastructure (e.g. hydrogen fuel infrastructure) is needed, government may need to either invest directly or provide incentives for private sector investment.
- In cases where networks are important (e.g. transmission lines), government may have a role in creating shared rules of access and shared protocols that allow multiple firms to participate in a competitive fashion. In many cases existing rules favor well-established technologies and thus act as a barrier to innovation. Maintaining openness to new entrants needs to be included in the design and redesign of regulation.
- In cases where there are considerable health, environmental and/or safety concerns, clear governmental rules for risk evaluation and risk regulation are necessary for the private sector to have the confidence to invest in innovation.

Sequencing and Synchronizing Supply-Push and Demand-Pull Policies

The division of efforts between government policies to support R&D and market creation must be based on the stage of technology development and opportunities for a particular technology and technological system. Evaluation is needed to determine what can be achieved through on-going public investments in R&D versus what can be achieved through the learning-by-doing, economies of scale, and growing private sector R&D that accompany a growing market.

- Early investment in technology demonstration and limited deployment can provide feedback to improve the technology and to learn about the institutional and policy adjustments and physical infrastructure needs for a new technology.
- Care should be taken not to make large investments in the deployment of early vintages of a technology.
- A tax (on a fuel and technology specific basis) that internalizes the externalities associated with energy production and consumption would change the relative attractiveness of specific energy technologies, and increase the niche markets for emerging energy technologies.
- If technologies are serving niche markets, businesses are established that can grow rapidly if the resolution of uncertainties proves that they should be deployed widely. Thus, in this environment of uncertainty in terms of when and to what extent alternative energy technologies will be needed to address critical national interests, an appropriate strategy is to support both R&D and emerging technologies in niche markets.
- The inherent uncertainty in outcomes calls for frequent re-evaluation of the portfolio of R&D and market creation policies for any given technology.

Strengthening Competitiveness through Economic and Technology Policy

One of the great strengths of the U.S. national innovation system is its intense competitive environment that includes competition between multiple firms, multiple technologies, multiple sources of funding for R&D, and multiple performers of R&D

- Policymakers should consider how the full range of government policy influences the competitiveness for a given sector and technology. This includes the supply-push and demand-pull policies discussed above as well as other policies such as anti-trust policy and intellectual property rights.
- Many areas of the energy sector are oligopolistic in structure, thus requiring careful attention to competition in government sponsored R&D policy. Avenues available to support competition include: support of start-ups with viable technologies; competition between multiple energy technologies for R&D funding; and allowing foreign-based firms that have substantial manufacturing or R&D facilities in the United States to compete for U.S. R&D funding.

Intellectual Property Rights

Intellectual property rights (IPR) policy for promoting innovation is sector specific. In some cases, broad patent protection contributed to rapid innovation; in others a relatively weak IPR framework during the early stages contributed to technology transfer and competition, and thus innovation. In all cases, the changes during the 1980s in U.S. laws governing private ownership of IPR from government sponsored research have been instrumental in advancing public-private partnerships and university-industry and national laboratory-industry technology transfer.

- As DOE moves to toward the greater use of R&D partnerships with universities and private firms, care must be taken prevent the monopolization of pre-competitive technology or of basic infrastructure technologies that are necessary for multiple firms to develop applications.

Strong Mission for Sustained and Strategic Support

Broad-based political support identifying a technological area as critical to national interests provided the underpinning for the sustained and multi-faceted effort needed for successful technology innovation.

- Innovation in the energy sector would be enhanced by further development of a national consensus on not only the importance of energy technology innovation for addressing security and environmental concerns, but also on the level, direction and types of policies that are necessary.
- Government investment levels in the energy sector should be commensurate with the public interests at stake.

Design Policy to Avoid Government Failure

Government intervention to overcome market failure is only valid if it can do so without substantial "government failure." In technology policy, the two major problems with government intervention are "picking winners" and "corporate welfare."

- Government failure can be avoided by designing policies to require and promote competition, and by increasing private sector cost-sharing in R&D programs as technologies move closer to commercialization.
- Re-evaluation of long-term programs mid-stream and sunset clauses can be used to avoid the establishment of permanently subsidized industries.

Chapter 1: The Role of Government in Technology Innovation: Guidance for Government Policy in the Energy Sector[1]

Vicki Norberg-Bohm

Introduction

Fundamental changes in energy technologies and energy systems are needed to address the energy challenges of this century, which include security of energy supplies; social and economic development; security from the spread and use of nuclear materials; and management of the environmental problems associated with energy use, including local and regional air pollution and greenhouse-gas induced climate change. There are several issues to consider in determining how government can most effectively promote the technology innovation that will be needed to address these challenges. What should the government's role be in the development and deployment of new energy technologies? What is an appropriate role for government at the different stages of technology innovation? What market, industry sector, and technology characteristics influence the appropriate role of government for different types of technology? And when there is a role for government, what strategies are most effective?

On February 11, 2002, the Energy Technology Innovation Project of the Belfer Center for Science and International Affairs at Harvard University hosted a workshop*, The Government's Role in Technology Innovation*, to bring analysis and debate to bear on these questions. The workshop was sponsored by the Office of Energy Efficiency and Renewable Energy, Department of Energy, and the National Renewable Energy Laboratory. The workshop was organized around six presentations by experts from academia, with discussants from government and industry, and attended by 80 senior executives and managers from government, industry and the NGO community. The presentations and subsequent papers, which are included in this volume, focused on the role of government in technology innovation in four sectors and the effectiveness of previous government policies and programs to promote innovation in both defense and civilian technology. Specifically, we covered the following topics: U.S. technology policy since WWII (Alic, chapter 2); funding the transition from invention to innovation and the Advanced Technology Program (Branscomb and Auerswald, chapter 3); computer and information technologies, including

[1] This synthesis chapter draws on the work by the other authors in this volume, including John Alic, Ashish Arora, Phillip Auerswald, Lewis Branscomb, Muriel Calo, Calestous Juma, and David Mowery. I am also grateful for the participation and insights provided by the discussants at the workshop, including Peter Bihuniak, Brent Erickson, John Gibbons, T.J. Glauthier, Philip Sharp, and Robert Walker. Finally, the workshop participants, too numerous to name, provided insights from the public, private and NGO sectors. This project was sponsored by the Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy and the National Renewable Energy Laboratory. This project also draws on research sponsored by the Integrated Assessment program, Biological and Environmental Research (BER), U.S. Department of Energy (grant DE-FG02-99ER62747). Finally, I benefited substantially from insightful comments on this chapter by John Alic, Bill Babiuch, Lewis Branscomb, Robert Friedman, Rene Kemp, and Douglas Norland.

semi-conductors, computers, software, and the Internet (Mowery, chapter 4), agricultural biotechnology (Juma and Calo, chapter 5), industrial chemicals, including synthetic dyestuffs, polymers, and process engineering (Arora, chapter 6), and the power sector, including gas turbines, wind turbines and solar photovoltaics (Norberg-Bohm, chapter 7). By drawing on the experience in a number of sectors and with a number of policy approaches, the goal of this project was to learn lessons that are applicable to the energy sector.[2]

Although there is a consensus in the United States that government should support basic R&D, there remains considerable controversy over how and under what conditions government should be involved in applied R&D, demonstration, and deployment. This controversy is illuminated by contrasting quotes from discussants at the workshop. The honorable Robert Walker[3] stated unequivocally that government has no role in deployment of civilian technologies, "I can't see how the government ever has a role in deployment unless the government itself is the operator of a function in society. And defense, of course, is the supreme example where indeed demonstration and deployment is essential." Dr. Jack Gibbons[4], while recognizing there may be a government role in deployment, cautioned, "Support for deployment can lead to a permanently subsidized industry... like corn methanol." While agreeing that permanent subsidization of markets is not a good idea, Dr. Bihuniak[5] suggests the road to commercializing emerging energy technologies will, in some cases, require subsidies in early stages, "In the case of technologies that are on the cusp of large scale commercial reality, I think it is important to provide market stimulation because that will create the scale that will drive cost reduction, that will open up markets that don't require subsidization." By looking at the development of U.S. technology policy broadly, and at several industrial sectors in specific, this project aimed to shed light on the appropriate role for government in the various stages of technology innovation in the energy sector.

The overarching conclusion of this project is that in addition to support for R&D, many other government policies are needed to promote successful technological innovation, including policies that support demonstration and deployment. This synthesis document begins by examining the patterns of government involvement in the four sectors that lead to this conclusion, as well as sectoral factors that account for the different patterns of government involvement in the sectors examined. Based on this comparison, the next section presents the key findings of the study for the design of energy technology policy. It provides lessons in the following areas: the need for multiple policies that influence both the supply of technology (supply-push policies) and the demand for the technology (demand-pull policies); the design of supply-push policy, including support for long-term R&D, the role of

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[2] The classic work on this topic is Nelson 1982. Many of the findings in his conclusion resonate with the findings of this study. Since this 1982 study, there have been some significant changes in laws governing public-private R&D collaborations and intellectual property rights resulting from these collaborations. These changes are captured in the more recent work by Mowery and Nelson (1999). The current volume builds on this previous work, both in terms of the specific cases and in the overall analysis. The major contribution of this volume is twofold: a focus on the energy sector and how to draw lessons from other sectors that are appropriate to policy in the energy sector, and within this context, an effort to further understand government's role in applied R&D close to commercialization and in market creation.

[3] Former Congressman from Pennsylavia's 16th District.

[4] Science advisor to President Clinton, Former Director of the Office of Technology Assessment.

[5] Vice President for Research, BPSolar.

universities, public-private partnerships, and portfolios and performance measurement; the design of demand-pull policies, including niche market creation and complementary infrastructure; the sequencing and coordination of supply-push and demand-pull policies at different stages in the innovation process; competitiveness; intellectual property rights; strategic focus; and how to avoid government failure in efforts to overcome market failure. The paper concludes with a brief summary and a focus on two crosscutting themes – creating options and creating enterprises.

Overview of the Cases

Figure 1 provides a broad overview of the role of government in the four sectors examined in this report. Several important conclusions can be drawn from this comparison. First and foremost, technological innovation depended on government activities that influenced the supply of technology (supply-push policies) as well as government activities that influenced the demand for technology (demand-pull policies). The exception to this broad pattern was industrial chemicals, in which government policy had a more limited role, being a dominant factor in technological innovation in more limited circumstances. Second, policies that promoted competition, both inside and outside the normal sphere of technology policy, had enormous impacts on technological innovation and the commercial success in these sectors. Third, policies influencing intellectual property rights (IPR) were important in all instances, although, as will be discussed below, in some cases strong IPR stimulated innovation, while in others weaker IPR regimes contributed to competitive forces which in turn supported innovation. Finally, a strong sense of national mission contributes to the development and implementation of a successful policy strategy. Each of these issues is discussed in depth in the following section, along with their implications for energy technology policy.

It is important to note that Figure 1 represents a summary of policy implemented over decades. Not all mechanisms were used simultaneously. In the discussion in the next section, it will become clear that effective policy is sectoral and technology specific, changing overtime as technology moves from invention to commercialization, and then through subsequent innovation cycles for a particular technology. The marks in the matrix simply indicate that this category of policy was of high importance at some point in the innovation process.

While shared patterns emerge across sectors, the differences in sectors are apparent as well. Previous research has concluded that "Policies associated with the development of a strong industry vary significantly from sector to sector, in scope, in kind and in impact"(Mowery and Nelson, p.376, 1999b).[6] These cases confirm that conclusion. As noted in Figure 2, key differences across sectors occur in the types of externalities, market characteristics, and complementary and enabling infrastructure (both institutional and physical) as well as the national interests driving government involvement. These factors help explain the similarities and differences in government involvement in each of the sectors. Specifically, they illuminate: (1) why different sets of demand-pull policies were employed along with different levels of intervention throughout the innovation cycles in computers/information technologies, agricultural biotech, and the power sector; (2) the "exceptionalism" of the

[6] This was also a key finding of Nelson 1982.

industrial chemicals sector and why this may be changing; and (3) why very different approaches to IPR resulted in successful innovation in computers/information technologies and agricultural biotech.

Figure 1: Policies Influencing Technological Innovation: A Comparison Across Sectors

	SECTOR			
POLICY MECHANISMS	Computers and Information Technologies	Agricultural Biotech	Power Sector Technologies	Industrial Chemicals **(a)**
SUPPLY PUSH				
R&D Funding – Defense	●		●	**(b)**
R&D Funding – Civilian	●	●	●	**(c)**
DEMAND PULL				
Procurement – Defense	●		**(e)**	**(b)**
Procurement – Civilian	●		●	
Regulation/Deregulation	●	●	●	**(d)**
Standardization	●	●	●	
Subsidies/Tax Breaks			●	
ECONOMIC POLICY				
Anti-Trust Policy	●			
Intellectual Property Rights	●	●	●	**(b)**
Import Policy	●			

(a) There was limited governmental involvement in chemical sector.
(b) Synthetic rubber is an exception; government provided R&D funding and was a large procurer during WWII, and did this in a way that required sharing IPR
(c) Although there was limited direct support, government has provided substantial support of university research in relevant fields.
(d) Environmental regulation has influenced innovation in this sector over the past three decades, although there is no in-depth research on this topic, overall it does not appear to be a dominant factor.
(e) Of importance in initial development of some technologies.

Figure 2: Sectoral Factors Influencing Role of Government in Technology Innovation

	SECTOR			
SECTORAL CHARACTERISTIC	**Computers and Information Technologies**	**Agricultural Biotech**	**Power Sector Technologies**	**Industrial Chemicals**
National Interest	Defense, Economic Competitiveness	Food Security, Economic Competitiveness	Energy Security	(a)
Environmental Externalities	toxic pollution in manufacturing, but not driving issue	potential ecosystem disruption and human health impacts	air pollution, climate change	Pollution, but not driving issue for broad-based innovation
Market characteristics	specialty goods and commodity goods	commodity good, sometimes tied to specialty good	electricity is commodity good	specialty goods and commodity goods
Complementary and Enabling Infrastructure – Institutional	need for network protocol	need for safety protocol	rules for access to power network; knowledge about resource availability; environmental regulation	
Complementary and Enabling Infrastructure – Physical	Internet network		power network	

(a) The paper on the chemical sector suggests a limited national interest, with the exception being the involvement in synthetic rubber and high-octane fuel in WWII.

Designing Policy for Technology Innovation

Technological innovation encompasses not simply inventions, but also the process of going from invention through commercialization and into widespread adoption. This set of case studies is focused on this full set of activities, often referred to as the process of innovation and depicted as an "innovation pipeline."[7] In other words, we are concerned not simply with invention, but with how new scientific and technological ideas are transformed into commercially successful products. In sum, in the discussion that follows, successful innovation is defined not simply as technological success, but includes commercial success, i.e. adoption of the technologies by end-users.

Multiple Policies: Simultaneous Support for Supply-Push and Demand-Pull Policies

Multiple policies, working together in a synergistic package (if not always designed as part of a cohesive strategy) were the key to successful technological innovation, and particularly to the success of radical technological transformations in computers/information technologies, agricultural biotech, and the power sector. This included policies directed toward both supply-push and demand-pull.[8]

Would these successes have occurred regardless of this broad-based governmental support? Although counterfactual history can never be disproven, it is fair to say that this is unlikely. In these cases, while the U.S. and other OECD nations often started with similar technological capabilities, the U.S. emerged as a technological leader due in large part to multiple government actions that influenced the innovation system for each of these sectors.[9] Simply put, investing in R&D alone was not a strategy employed, nor a strategy that would have been effective in three of the four sectors examined in this volume. The reasons for the exceptionalism of the industrial chemical industry will become clear in the more detailed discussions in the sections on supply-push policies and demand-pull policies.

Beyond this empirical evidence, the need – at least in some sectors and for some technologies – for multiple government interventions that occur at different stages in the innovation process can be understood in terms of market failures that result in underinvestment by the private sector in research, development, and/or deployment of new technologies. This is summarized below and discussed in greater detail by Norberg-Bohm in Chapter 7. The factors leading to under-investment in R&D – knowledge spillovers and uncertainty – are well-established and provide the underpinning for the national consensus that government has a large role to play in this stage of the innovation process (Cohen and Noll 1991a). For the transition from invention to innovation, recent research has suggested an "innovation gap", which includes gaps in funding, information and trust.[10] Branscomb and Auerswald (Chapter 3) show that government is one of the key actors that fills this gap, and that the risks and uncertainties at this stage are too high for venture capital to substantially replace government funding. Costs not included in the market price, i.e. externalities such as

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[7] The innovation process is discussed in Chapter 3 (Branscomb and Auerswald).
[8] In Chapter 2, Alic reviews the strengths and weaknesses of a number of specific policy tools.
[9] This issue is discussed in depth in Mowery and Nelson 1999.
[10] Preston 1997; Branscomb and Auerswald 2001.

environmental impacts and national defense, act throughout the process of innovation and are a particularly strong barrier to successful technological innovation during the period spanning pre-commercialization through early adoption. This is discussed in more detail in the section on technological learning. Finally, large transaction costs and/or the divergence between public and private discount rates can act as a barrier to technology adoption. For technologies with these characteristics and large public benefits, government may have a role in supporting widespread diffusion.

The virtual cycle that can be created through simultaneous support for supply-push and demand-pull policies is illustrated by the case of wind turbines. As outlined by Mr. Dan Reicher[11] at the workshop,

> "I think we tend [wrongly] to look at this R&D process as quite linear. In fact, at least in the area of energy R&D we go to demonstration, we go to early deployment, we see what works, we see what doesn't work, and we go back into the R&D stages in a very significant way. It is a complicated system but one that I think we need to take better account of, and it does argue for some support for at least modest demonstration, and some support for early deployment ... Wind is a great example of that. The turbines have gone out. We've seen what works; we've seen what doesn't. They've gone back to materials work, to blade design and then to some big revolutionary changes. As we've seen that gearboxes have problems out in the field, people are moving to direct drive turbines. So there is very much a cyclical nature to this that really has to be taken into account in our thinking."[12]

This example of wind turbines illustrates the interconnectedness of the stages of innovation and the way in which government can play an effective role through support for R&D, demonstration and deployment. The case of wind turbines is discussed in greater length by Norberg-Bohm, Chapter 7.

Supply-Push Policies

Long-term R&D Funding

Government support for basic and applied R&D has laid the groundwork for the successful development of computer and information technologies, agricultural biotech and power sector technologies examined in this volume. This was done through multi-decadal investments in the scientific and technological knowledge needed to develop these technologies. In these cases, R&D funding was universally important in the early stages, with inventions and initial technology applications often occurring decades before widespread diffusion.[13] Furthermore, the government invested in the on-going scientific and

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[11] Vice President, Northern PowerSystems, Managing Partner of New Energy Capital, Former DOE Assistant Secretary for Energy Efficiency and Renewable Energy.

[12] Despite an on-going tendency to look at innovation as a linear process, there has been progress in terms of policy initiative, including the Advanced Technology Program (ATP, see chapter 3) and some practices in the energy sector (chapter 7).

[13] In addition to the evidence for this in the cases, this is also discussed by Alic, Chapter 2.

technological breakthroughs that were needed to reduce costs and improve the quality (e.g. reliability, capability, environmental impacts) of new technologies, thus ensuring that they meet public interests and are attractive to private users. Even for the industrial chemical sector, in which government support was not a critical factor, broad government support for the underlying science was important to innovation in this sector (Arora, Landau and Rosenberg 1999). Furthermore, Arora (Chapter 6) argues that changes in the structure of the chemical industry may be creating a need for greater government R&D investments in the future. In sum, R&D portfolios must include investments in the basic scientific and technological research underlying breakthroughs in specific fields as well as ongoing investments in applied RD&D that is too risky for private firms to undertake on their own.[14]

Public-Private Partnerships

Considerable enthusiasm for public-private partnerships was expressed at this workshop. Dr. Jack Gibbons stated, "Most success comes from public-private partnerships. This is a reality, so lets stop debating this." Mr. Brent Erikson[15] also weighed in on this topic, " If you look across our economy the most successful sectors, almost without exception, have resulted from public-private partnerships. So I think the notion that somehow government shouldn't be involved in innovation and partnerships with the private sector is simply false, and we should just stop talking about it because the facts belie that to be the case."

Although public-private partnerships were implicit in the discussions in biotechnology and information technologies, they were analyzed in terms of policy design only in the chapter on the power sector (Chapter 7). From that chapter and the discussion at the workshop, several key design lessons emerge. First, public-private partnerships should set "stretch" but reachable technological targets. Second, public-private partnerships must be designed differently for different stages in the innovation process. Cost-sharing should increase as projects move closer to commercialization, although different levels may be appropriate for small versus large firms. IPR policy may also differ, with government wanting more of the long-term R&D results to remain in the public sphere or to be broadly licensed. Third, public-private partnerships should be used for goal setting as well as implementation. Fourth, these partnerships should engage not only the Department of Energy and private firms, but also universities and national laboratories. In the goal-setting process, they should also engage additional stakeholders such as NGOs and EPA, which have relevant knowledge and interest in the technology under development.

The Role of Universities

Much of the R&D discussed above was undertaken in universities. The focus of U.S. universities on industry relevant knowledge is one of the hallmarks of the successful U.S. innovation system. The involvement of universities contributes not only through the

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[14] In terms of supply push, Alic, Chapter 2, outlines in detail the numerous policies, in addition to government-sponsored R&D, which can influence the total level of R&D spending (both public and private). For a discussion of government's role in supporting mission-oriented basic R&D, see Holton and Sonnert 1999, Branscomb et al. 2000.

[15] Industrial and Environmental Section, Biotechnology Industry Organization (BIO).

technological and scientific assets they bring, but also through the training of the workforce needed for designing and using emerging technologies, and as a launching pad for high-tech companies. In the case of government-funded applied research that is closer to commercialization, while it makes sense to do this within the context of public-private partnerships with much or all of the research undertaken by the private sector, there remains a role for the university. In this context, universities can serve both as a laboratory for more risky research and a training ground for the next generation of appropriately skilled workers.

Portfolios and Performance Measurement

In looking at government R&D investments, it is important to expect success and failure – from both a technological and commercial perspective. Government should be making investments that the private sector finds too risky to undertake on its own and investments in technological options that will be able to address emerging problems that may not materialize as expected. Thus, government-sponsored R&D programs should not expect complete technological or commercial success; in fact excess success would be an indication that government is not taking enough risks. In practical terms, this means that the government R&D portfolio should be weighted toward riskier investments.

This has important implications for measuring outcomes, as required by the 1993 Government Performance and Results Act (GPRA), particularly in light of the increased priority that the Bush Administration has given to GPRA and performance-based budgeting.[16] First, program success should be measured at the portfolio level, and not at the level of individual projects. Second, technological success, even without market penetration, should be valued if it provides options for addressing potential future problems.[17]

Demand-Pull Policies: Creating Markets for Technological Innovations

While demand-pull policies played a role in all of the sectors, they were more prominent in some sectors than in others and the specific instruments varied considerably. As discussed below, this can be understood in terms of several sector specific characteristics including: relation to high-priority national missions such as defense, economic competitiveness, and environmental protection; the need for specific types of complementary and enabling infrastructures; and market characteristics.

For the computers and information technologies sector, both defense and civilian procurement played a role in market creation. Defense procurement provided the initial market, preceding the civilian market for each of the four technologies examined in this sector: semiconductors, computers, software, and the Internet. In all cases, except for semi-conductors, civilian procurement followed, being particularly important for innovation in computers, where by 1963 over 50 percent of university computers had been purchased by the government. In the case of the Internet, the National Science Foundation (NSF)

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[16] See Branscomb and Auerswald, Chapter 3, for a brief discussion of GPRA.

[17] This issue was discussed at great length at a recent EERE workshop, where attention was given on how to measure the "option value" of government R&D investments; see www.performance-measures.org/benefits-conference.

influenced its further development in several ways. NSF required that all "qualified users" be given access and that all providers use the standard network protocol TCP/IP. Furthermore, the NSF policy of excluding commercial users from the university-based, government funded infrastructure provided an incentive for the private sector to build a parallel infrastructure. Two aspects of the regulation of the telecommunications industry also helped. The first was the requirement for competition in long-distance and local markets, which resulted in the widespread availability of affordable leased lines. Second, unlimited time pricing on local phones increased the usage of the Internet.

For agricultural biotech, procurement was not important nor were subsidies and tax breaks; i.e. government did not provide any form of direct financial support for the market.[18] Because there is a well-developed private market in seeds, the success of agricultural biotech depended on easy access to this market. This was achieved in the United States through sector-specific standardization and regulation. Early in the evolution of the agricultural biotech industry, U.S. regulation defined products created through biotechnology as "substantially equivalent" to products produced through more traditional means. Furthermore, the three relevant executive agencies – USDA, EPA and FDA – created a coordinated review process, resulting in a relatively streamlined process for the approval of new biotechnology products.

In the chemical industry, except in the cases of military demand during WWII (synthetic rubber and high-octane fuel), demand-side government policies were not of great significance.[19] Rather, firms with both specialty and commodity chemical businesses were able to profit from private R&D investments through the sale of new chemical products in the private market. The exception to this is the importance of environmental regulation as a driver of a specific set of innovations in recent years.[20]

For the power sector technologies examined in this volume – gas turbines, wind turbines and solar photovoltaics – government procurement played a role in initial market creation. In the case of gas turbines, this was through the military purchase of jet engines, from which stationary gas turbines drew much of their early innovations. In the case of solar photovoltaics, this was for space applications and also through demonstration programs, which provided crucial markets for the early efforts for earth-based applications.[21] While these procurement programs had an important early role, it was subsidies, environmental regulation and restructuring of the power sector that played a more enduring role in expanding the market for power sector applications of these technologies. All three technologies required a restructuring of the electric power sector in order to compete with

[18] While farm subsidies clearly play an important part in the agricultural marketplace, they do not discriminate between genetically modified (GMO) seeds and non-GMO seeds.
[19] Alic (nd) suggests that the military may have been an important consumer of goods from the industrial chemical sector, contributing to the profitability that made internal R&D investments possible, if not a direct driver of R&D. Further investigation is needed to understand this relationship.
[20] This is mentioned in Arora, Landau and Rosenberg, p. 239, and again in the summary of the same book, Mowery and Nelson, p. 377. I am unaware of any in-depth analysis that shows how important this has been relative to overall innovation in industrial chemicals, although certainly there are many relevant anecdotes.
[21] Margolis 2002.

existing technologies.[22] Beyond this, the path for commercialization of stationary gas turbines differed from that of wind turbines and solar photovoltaics. Gas turbines were able to gain an initial private market based on a privately valued quality – fast start-up and shut-down that was needed for peaking power. In contrast, the other two technologies are valued primarily for their impact on public goods, specifically air pollution and energy security, and required subsidies to move through the learning process. While wind generated energy has now competitive in some markets, solar photovoltaics continue to require government support (e.g. subsidies and/or standards requiring its use).

Niche Market Creation

As technologies enter the marketplace, experience in manufacturing and using these technologies results in feedback loops that, when successful, result in increases in quality and decreases in price. These occur through learning-by-doing, learning-by-using, economies of scale, and on-going R&D breakthroughs. This process most often depends on finding early adopters for the technology, also known as a niche market, in which this learning process can occur.[23] As discussed above, this niche market was created in different ways in the four sectors examined in this volume. In some cases it depended on government procurement or government subsidies for a new technology. In others, government's role was limited to regulatory policies that structured the market

Four key lessons regarding demand-pull policies emerge from comparisons across these cases.[24] First, in cases where there is a private market willing to pay more for the qualities provided by the new good, such as the chemical industry, agricultural biotechnology and gas turbines, government will often be needed to structure regulations and standards, but not to provide direct support for niche markets. Because sectoral regulations are structured around existing technologies, and thus often act as a barrier to technological change, deregulation in telecommunications and electric power were essential elements for innovation in the Internet and alternative energy technologies, as was the development of a favorable regulatory system in agricultural biotech.[25]

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[22] This restructuring began in 1978 with the passage of the PURPA legislation that opened the door to small independent power producers selling power to the grid, and has proceeded through efforts over the last decade to foster competition in the wholesale and retail power markets. The ways in which this impacted technology innovation in the power sector are discussed in Chapter 7, and in greater detail in Norberg-Bohm 2001.

[23] The process of technological learning is discussed in greater detail by Alic in Chapter 2 and Norberg-Bohm in Chapter 7.

[24] Duke and Kammen (1999) engaged in an analysis of market transformation programs that resulted in five criteria for when government should invest in increasing demand. This paper takes issue with their second criteria, "the potential for relatively fast cost reductions as indicated by a favorable progress ratio and relatively low cumulative production to date." While this criteria would be necessary as an indication that demand-pull mechanisms may be appropriate, for a technology in this phase of learning further technology assessment is necessary to determine whether government investments are better spent in R&D or demand-pull, or some combination of the two.

[25] The chemical industry was never treated as a regulated monopoly, and health and safety concerns have been addressed largely through regulatory requirements that could be achieved through incremental innovations to existing technologies. Thus, demand-side policies were less critical to technological success in the industrial chemicals sector.

Second, when there is not a large enough market niche for the initial use a new technology based on qualities valued by the private sector, as was the case for computers, wind turbines and solar photovoltaics[26] *and* if there is a strong public interest in pushing the good through commercialization, then government will need to play an active role in creating initial markets for the demonstration and deployment of the technology. This initial market can put in motion the process of technological learning that is likely to improve quality and decrease cost. Furthermore, over the longer term this learning process may lead to a cost-competitive technology.

Third, government support for initial markets is even more crucial and may need to be of longer duration if the end-use of the product in question is a commodity good. This is the case in the power sector, where consumers purchase electricity and except for a limited number of "green" consumers do not pay attention to how the electricity is produced. When government provides market support through regulations or subsidies, it is important to design the policies in a way that promotes innovation (see sections below on competition and avoiding government failure).

Fourth, government support for niche markets can also support the public goal of economic growth and competitiveness. Early and/or large-scale deployment can create competitive advantages for firms and nations (see the case of computers and information technology, Mowery, Chapter 4). This is again related to the learning process, in which early experience with a technology provides the feedback loops necessary for commercial success. Furthermore, investments in technology development and manufacturing go where the market is; i.e. a nation's strong basic R&D alone will not stimulate the growth of businesses.

Complementary and Enabling Infrastructure

In assessing the need for government action to provide complementary and enabling infrastructure, several key lessons emerge. In all cases, the government through its support for research and teaching at universities contributed to the development of the human resources necessary for success. In short, a strong university system that focuses significant research on topics relevant to industry is a critical underpinning of an effective national innovation system. Not surprisingly, the rest is quite sector specific. In cases where physical infrastructure is needed, collective action problems can prevent it from being built by individual private parties. In these cases, strong public interest means that governments may want to invest in infrastructure or provide incentives for private sector investment. In cases where networks are important (e.g. the Internet and transmission lines), shared rules of access and shared protocols are needed to allow multiple firms to participate in a competitive fashion. In many cases rules will favor specific technologies and can act as a barrier to innovation. Maintaining openness to new entrants needs to be included in the design and redesign of regulation. Finally, in cases where there are considerable environment, health, or safety issues (EHS), government needs to implement regulations for determining what technologies create unacceptable levels of EHS risk and/or how specific technologies may be

[26]A niche market exists for solar PV, but it is not an adequate stimulus to bring about the innovations necessary to make solar PV competitive in the private utility market.

used. Clear rules for EHS risk evaluation and regulation are necessary for the private sector to have the confidence to invest in innovation.

Sequencing Supply-Push and Demand-Pull Policies

At each stage of technology development, the government needs to assess its role in both R&D and market creation. More specifically, a careful evaluation is needed of what can be achieved through on-going public investments in R&D versus what can be achieved through the learning-by-doing, economies of scale, and growing private sector R&D that accompany a growing market. Even before a technology is likely to be economically competitive in the energy sector, some investment in technology demonstration and deployment can be useful to provide the feedback needed to improve the technology and to learn about human and society interfaces with a new technology. Beyond proving technological success, this experience can start the process of learning about the institutional and policy adjustments and physical infrastructure needs for a new technology. However, there is a tension between these positive outcomes, and the potential to make large investments in early vintages and/or technologies that will never be economically competitive. In other words, there is a need to make a judgement about the ability of a growing market to set in motion a virtual cycle of improving quality and decreasing costs that eventually makes a technology competitive in the private market. Uncertainty in outcomes calls for frequent re-evaluation of the portfolio of R&D and market creation policies for any given technology.

Government intervention to make the private market internalize externalities would of course change the prices and relative attractiveness of specific energy technologies. Although energy prices currently do not reflect these externalities, concern and uncertainly about the impacts and severity of environmental and security issues associated with energy production and use are the main drivers of public investment in both R&D and market creation for alternative energy technologies. In this environment of uncertainty in terms of when and to what extent alternative energy technologies will be needed to address critical national interests, an appropriate strategy is to support both R&D and emerging technologies in niche markets. Prof. Lewis Branscomb outlined the rational and benefits of this strategy at the workshop:

> "The only sensible strategy is to identify every niche market there is. ... Let's push the technology along as fast as limited niche markets will allow it to be pushed. It's a heck of a lot better strategy than just doing the R&D and publishing it and waiting 20 years, because when the time comes when you need it, you've got the R&D, but you've got no business. And that business can grow very fast if its in place serving niche markets. ... So if I were judging the performance of DOE, I would ask have you identified the most promising alternative technologies for oil? If you have, have you identified the niche markets that can foster those technologies? Are those niche markets reasonably healthy and competitive on the world standard?"

Strengthening Competitiveness through Economic and Technology Policy

One of the great strengths of the U.S. national innovation system is its intense competitive environment. This competitive environment is composed of multiple firms, multiple technologies, multiple sources of funding for R&D, and multiple performers of R&D (see Alic, Chapter 2).[27] Technology policy is most effective when it strengthens competition (Mowery and Nelson 1999b). For example, Mowery (Chapter 4) concludes that a variety of the policies in the computers and information sector increased competitiveness, and that this was a strong factor contributing to successful innovation. Strong anti-trust enforcement as well as military R&D and procurement policy that required multiple suppliers contributed to low entry barriers for new firms and a high degree of inter-firm knowledge and technology transfer. Furthermore, the reliance on extramural R&D performers drew on the intense competitive environment of the U.S. private sector and universities. This latter factor was also important in contributing to the highly competitive environment in biotech. The highly competitive environment in the United States distinguished it from Japan and Europe and is one key reason for the comparative success of the U.S. information technology industry. In sum, the structure of R&D policy matters as much as the funding level. Innovation policy can and should be designed in ways that create a competitive environment.

The case of synthetic rubber, as discussed by Arora in Chapter 6, provides lessons about the limitations of technology policy that stifles competition. The Synthetic Rubber Research Program required all manufacturers to use a standard recipe as well as share knowledge about manufacturing. This combination of standard recipe and open access to knowledge increased the entry of firms in manufacturing, and thus contributed to process and incremental innovation, but suppressed radical innovation. This may have been appropriate to meet wartime needs, but provides clear lessons on how not to structure a policy aimed at radical technology innovation.

In energy technology policy, there has been an awareness of the need for competition, but a challenge in cultivating this for some specific technologies. This is due to the oligopolistic and global structure of some parts of the energy technology industry, which results in only a single U.S. manufacturer for some energy technologies. Government procurement for national security made it possible for the defense policy to be structured in a manner that required multiple firms and inter-firm technology transfer. This mechanism is likely to have limited, if any, applications in energy technology. Some avenues available in energy R&D funding include: support of start-ups when they appear to have viable technologies; competition between multiple energy technologies for R&D funding; making certain that U.S. firms are operating in an internationally competitive environment; and allowing foreign-based firms that have substantial manufacturing or R&D facilities in the U.S. to compete for U.S. R&D funding.

[27] See Alic (Chapter 2) for a discussion of the U.S. national innovation system and Mowery (Chapter 3) for competition as key element in innovation in computers and information technology.

Intellectual Property Rights

In computer and information technologies, agricultural biotech, and the power sector technologies, as well as for civilian technologies more broadly, changes during the 1980s in U.S. laws governing private ownership of IPR from government sponsored research have been instrumental in advancing public-private partnerships and university-industry and national laboratory-industry technology transfer. These legal changes, which included the Bayh-Dole Act and the Stevenson-Wydler Act, have allowed non-profits, small firms, and universities to maintain IPR for government funded projects.[28] They also set the groundwork for the productive relationships between universities and the private sector in biotech and information technology. These changes made participation in government sponsored R&D programs and particularly public-private partnerships attractive to private firms. This policy shift in the 1980s was clearly beneficial to civilian technology innovation.

In some sectors, firms depend on patent ownership for profitability. IPR policy needs to strike a balance between this private interest and the public interest in a relatively broad dissemination of intellectual property. Because of this tension, there is not a simple relationship between the strength of IPR regimes and innovation. A relatively weak IPR framework in the early stages of semiconductors and computers, due to antitrust enforcement and military procurement, contributed to innovation in those technologies. In the case of the Internet, much of the IPR was in the public domain, including the basic network protocol. Again, this institutional setting stimulated technology transfer and associated innovation. Thus, in the case of computers and information technologies, Mowery concludes that a relatively weak system of IPR may have been helpful for the new industry. In contrast, a strong IPR framework, in which private companies and universities can obtain utility patents for living organisms,[29] was a key factor in stimulating innovation in biotech.

This sector specificity makes it difficult to make broad-based recommendations for the energy sector. A guiding principle would be to prevent the monopolization of pre-competitive technology or of basic infrastructure technologies that are necessary for multiple firms to develop applications. Thus, as DOE moves toward the greater use of R&D partnerships with universities and private firms, care must be taken in agreements on ownership of IPR.

Strong Mission for Sustained and Strategic Support

Radical technological transformation of a sector is a long-term process, on the order of 50 years of more. Even moving from introduction to widespread use of new technologies that do not require overall systems changes can take 10 years or more, given the lifecycle of consumer goods and capital stock. Sustained government policy is thus needed over a long time-period for successful innovation and technological transformation in the energy sector.

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[28] These are discussed in Branscomb and Auerswald, Chapter 3. It is DOE practice to allow large firms to petition to maintain IPR in cost-shared projects.

[29] The laws allow for the patenting of a living organism upon meeting patent requirements that would apply to a mechanical invention. A utility patent can protect any plant having an inserted gene, rather than a single variety containing that gene. It also protects hybrid varieties. See Juma and Calo, Chapter 5.

In order to achieve sustained government support, a technology or sector must be viewed as critical to national interests. For computers and information technologies, this was initially through their use in defense and later due to their importance to economic competitiveness. Biotech was early on recognized as a critical technology for national economic competitiveness.

The broad-based political support that accompanies a critical national interest makes it possible to develop the long-term R&D funding and the other policies necessary to stimulate innovation. In other words, once a technology is established as a strategic technology, it is possible to support the co-evolution of technology and institutions that are needed for successful technological innovation. Under these conditions it is also easier, especially if there is strong executive leadership, to create the interagency cooperation that is most often necessary for radical technological transformations.[30]

In the case of energy, significant technological transformations are likely to involve the activities of many agencies in addition to DOE, including the Environmental Protection Agency, the Department of Agriculture, the Department of the Interior, and the Commerce Department. In the case of energy, several key national interests are at stake, including security of energy supplies and environmental concerns. While there is a growing agreement on the importance of energy technology innovation to our long-term national interests, there is little agreement about the level of effort or specific directions that need to be taken. Progress on this front may be needed as a pre-cursor to a more effective national energy strategy.

Designing Policy Mechanisms to Overcome Government Failure

Designing public policy to effectively address market failures throughout the process of technological innovation remains a challenge. Previous efforts by government to intervene beyond R&D have often failed. There are some spectacular examples in the energy sector, most notably synfuels. The cases reviewed in this volume demonstrate that government can effectively intervene throughout the innovation process. In these cases, government policy was able, at least in the large, to avoid the pitfalls of "picking winners" and "corporate welfare" associated with government failure.[31] The discussion above has already outlined elements of a successful technology policy design, but it is worth reviewing these through the lense of designing policy to prevent government failure.

"Picking winners," i.e. government choosing specific technological trajectories, can be avoided during the R&D phase by supporting a portfolio of technologies and multiple firms through a competitive bidding process, thus creating an environment that results in multiple rather than single technological options. It can be avoided during demonstration and deployment by designing policies that again require competition, between technologies and

[30] Interagency cooperation is often problematic in the United States. Dr. Gibbons made this point, stating that the U.S. "needs porous walls in our stovepipes."
[31] For a review of these issues, see Margolis 2002. For a more thorough treatment of the issue of government failure in commercial R&D, see Cohen and Noll 1991b.

firms. Ideally, these policies set framework conditions, either through economic mechanisms or regulatory requirements, that allow any technology that can satisfy the public interest (e.g. reduced emissions or improved security of energy supplies) to compete on a level playing field. Furthermore, to protect against picking the wrong technology, it is important not to bias technology policies only toward existing firms as radical technological innovations often come from new entrants. This set of explicit recommendations is basically a reiteration of the discussion on the importance of competition for successful technological innovation.

The second major concern is "corporate welfare," i.e. that government investments will replace private sector investments rather than complement them or even better, stimulate greater private investment in the public interest. In more basic or pre-competitive R&D, i.e. R&D that is five or more years from commercialization, this is less of an issue as it is clear that the private sector under-invests in this type of R&D. The concern of corporate welfare occurs in R&D that is closer to market and in demonstration and deployment programs. This problem can be avoided in part through the recommendations for competitive approaches described above. It may be further ameliorated by requiring increasing private sector cost-sharing for R&D and demonstration projects as a technology moves closer to commercialization, and having sunset clauses for subsidies.

These potential government failures – of picking winners and corporate welfare – cannot be ignored. But good policy design can prevent or minimize these concerns. Thus, government failure is not a reason to avoid action, but a reason to act well. As stated by Mr. Glauthier[32] at the workshop, "Energy markets are the creation of a complicated web of policies. So, market demand is not a true signal of either private or social demand. Government policy already shapes technology innovation in the energy sector – there is every reason to direct it toward public interests."

Conclusion

Based on a historical examination of the government's role in technology innovation in several sectors, covering experience in both defense and civilian technologies, this paper has drawn insights into the focus and design of government programs to promote energy technology innovation. The broad lesson to take from this study is that a successful innovation strategy requires multiple policy approaches spanning many spheres. In order to support the emergence of new energy technologies, government must support knowledge and technology development, as well as support markets for emerging technologies. Furthermore, successful innovation is dependent on policies that influence the competitiveness of the industry sector, intellectual property rights, and the development of supporting physical and institutional infrastructure.

The specific insights garnered for the energy sector are summarized in the executive summary of this volume. Thus, in closing this paper, the focus will be on two crosscutting themes – creating options and creating enterprises. These themes, while frequently mentioned throughout the discussion, are highlighted in closing due to their overall importance to the task of innovation in the energy sector.

[32] Director, Electricity Innovation Institute, Electric Power Research Institute.

The government's role in pursuing energy technology innovation is to a large extent to provide multiple technological options for the future. For example, currently fossil fuels are relatively inexpensive and widely used in the United States, but there are a number of future contingencies that could change that, e.g. changes in world oil markets or in policies for addressing climate change. Current investments in non-fossil energy technologies are being made in large part to be prepared to address these contingencies, i.e. to create option value. It is customary to think of investments in R&D as creating option value. This paper shows that in some cases targeted investments in supporting market demand is also a necessary part of a strategy of creating options. For technologies without a private niche market, these investments are necessary to start the learning process that is a crucial part of successful innovation. Specifically, investments in early markets make it possible to: improve quality and reduce costs; learn about and begin to resolve physical and institutional infrastructure issues associated with a new technology, and establish businesses that can expand rapidly if the option is needed in the future.

The second crosscutting theme, enterprise development, was implicit in much of the discussion, but deserves more explicit treatment.[33] Notwithstanding the need for active government support, energy technology innovation takes place largely in the private sector. Successful innovation is thus dependent on creating an environment that rewards innovative high-tech start-ups as well as greater innovation in established firms. In the other sectors examined in this volume, several policies proved important to the overall innovative environment for the private sector, including anti-trust policy, intellectual property rights policy, and tax policy related to R&D investments. The structure of government R&D and procurement policies also mattered; policies that fostered competition were most effective in supporting the development of innovative enterprises. Furthermore, support for problem-focused basic and applied research in universities was an important stimulus for high-tech start-ups. Further investigation into the current incentives and barriers for innovative start-ups in the energy sector and for innovation in the existing energy technology firms would be fruitful for developing specific policy recommendations on increasing the innovative capacity of the energy sector.

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Chapter 2: Policies for Innovation: Learning from the Past[34]

John A. Alic

> [R]evolutions … occur in discrete rushes which are separated from each other by spans of comparative quiet. The process as a whole works incessantly however, in the sense that there always is either revolution or absorption of the results of revolution ….
>
> Joseph A. Schumpeter [35]

As Schumpeter implies, technology evolves through a process resembling that which paleontologists call punctuated equilibrium. Radical innovations, relatively rare, interrupt and disrupt what would otherwise appear as a continuous flow of small, incremental changes: an increase by a percentage point or two in the efficiency of a jet engine's compressor stage; an improvement of a few percentage points in the production yield of a semiconductor fabrication line; a reduction from 13 to 9 parts in an automobile door assembly. Amidst this sea of incremental change, radical innovations — the jet engine itself, the microprocessor, "lean production" in the auto industry — stand out like rogue swells amidst an ocean of wavelets.

Major innovations come in two varieties. They may follow from a discrete invention, the jet engine or integrated circuit (IC). Alternatively, they emerge through the accretion of incremental changes which, like ice crystallizing from water, eventually yields something recognizably new and different — lean production or the Internet. Wide-area computer networks and ultimately the Internet resulted from the confluence of multiple streams of innovation in software, hardware for both digital processing and data transmittal (e.g., fiber optics), and systems. Many people contributed, some in big ways, others in small. Much the same is true of lean production, where contributions came not only from engineers and managers but from factory workers.

Innovations may qualify as "new" in several senses. Jet engines and gas turbines operate on a thermodynamic cycle patented in 1872, 60-some years before test-stand demonstration of working powerplants functioning on these principles. For the jet engine, demonstration constituted invention, reduction to practice innovation. The microprocessor was the result of a pure exercise in engineering design, the application of existing knowledge in an unprecedented way. Invention and innovation coincided. Unlike the jet engine, there were no major technical problems to overcome. Responding to a customer request for a set of

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[34] This paper is based in part on "Technology Policies for Reducing Greenhouse Gas Emissions: A Taxonomy," report to The H. John Heinz III Center for Science, Economics and the Environment, Washington, DC, February 1999, available at <www.heinzctr.org>. While the author is solely responsible for the contents, the paper has benefited from ongoing work with David C. Mowery for the Pew Center on Global Climate Change and from notably helpful comments by Vicki Norberg-Bohm.

[35] Capitalism, Socialism and Democracy (New York: HarperPerennial, 1975 [1942]), p. 83.

specially-designed IC chips for a desktop calculator, Intel engineers proposed instead a processing unit that could be programmed, via software permanently stored in memory, to emulate a calculator.[36] They had no notion where their design would lead; the idea was new, but it was simply a shortcut, a way of replacing several special-purpose ICs with a single chip, not yet the idea of a computer-on-a-chip. The invention of the microprocessor shows that even today, when science-based developments seem to be everywhere, radical innovations can appear without anything that might be called research.

Diffusion and adoption are almost invariably slow. Large numbers of people and organizations, variously welcoming or resistant to change, must learn how the innovation works and what it can do for them. Most of this learning is, a matter of trial-and-error and trial-and-success. Lessons must be extracted and absorbed, fed back into design and development, production operations and organizational practices. Continuing learning stimulates technical improvements which in turn accelerate adoption. Considerable time may thus elapse before the full blossoming of an innovation. For the microprocessor and the personal computer (PC), the 1970s were years of learning by both producers (what did customers want?) and users (what could these new devices do?). At first, much uncertainty surrounded both questions. Since hobbyists had purchased many of the early PCs (you could build a Heathkit), speculation centered on applications in the home. Would PCs be used for keeping address books? Kitchen recipes? Some observers thought the market would resemble that for fancy cars and swimming pools, fueled by conspicuous consumption. Office automation did not get much attention until the appearance of low-cost, easy-to-use software for word processing in the early 1980s. As businesses realized that PCs could replace dedicated word processing equipment (which in many offices had just begun to supplant electric typewriters), sales rose and other office applications (e.g., spreadsheets) followed. Only then did the retail market boom, as people who had learned to use PCs at work bought them for their homes. As this example shows, diffusion of even the most radical-seeming innovations is paced by often-meandering search processes through which applications, many of them initially unforeseen, are uncovered and explored.[37]

Jet engines and gas turbines illustrate the mutual reinforcement of evolutionary technical development and market expansion over a much longer period, more than 60 years. A continuing stream of mostly incremental performance improvements, many resulting from military R&D and procurement, led to increases in efficiency and durability great enough by the 1970s that gas turbines became feasible for standby electric power generation; base-load applications followed in the 1980s.[38] No one in the 1950s, when military jets guzzled so much fuel that fighter planes could travel little more than 100 miles before being forced to

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[36] William Aspray, "The Intel 4004 Microprocessor: What Constituted Invention?" IEEE Annals of the History of Computing, Vol. 19, No. 3, 1997, pp. 4-15.

[37] Paul Ceruzzi, "An Unforeseen Revolution: Computers and Expectations, 1935-1985," Imagining Tomorrow: History, Technology, and the American Future, Joseph J. Corn, ed. (Cambridge, MA: MIT Press, 1986), pp. 188-201, gives many examples contrasting anticipated with actual events in the development of computing.

[38] Robert H. Williams and Eric D. Larson, "Aeroderivative Turbines for Stationary Power," Annual Review of Energy, Vol. 13, 1988, pp. 429-489. For a reasonably intelligible treatment of improvements to a particular powerplant over time, see M. Badger, A. Julien, A.D. LeBlanc, S.H. Moustapha, A. Prabhu, and A.A. Smailys, "The PT6 Engine: 30 Years of Gas Turbine Technology Evolution," Transactions of the American Society of Mechanical Engineers, Journal of Engineering for Gas Turbines and Power, Vol. 116, 1994, pp. 322-330.

turn around and head for home, would have envisioned such outcomes, any more than developments in computer networks during the 1970s sparked predictions of an Internet "revolution."

Much innovation is invisible except to experts (aerodynamic improvements to gas turbine blades), takes place through processes that come together in unexpected ways (the Internet), has little to do with science or research (the microprocessor and PC). The unpredictable nature of innovation suggests that government policies should foster the technological equivalent of biological diversity, encouraging wide-ranging exploration of alternative pathways with eventual selection through competition rather than bureaucratic or political choice.

Technology Policies

Table 1 groups 15 policy tools into three broad categories:

1. Direct funding for technology development;
2. Measures that induce private spending or subsidize production, directly or indirectly; and
3. Diffusion-related policies that foster applications through information and learning.

Although the second of these categories is especially miscellaneous, the grouping lends a bit of structure. Because there is no standard set, other analysts might choose a different list than appears in Table 1, and advantages and disadvantages other than those included in Table 2. Note that the two tables exclude regulatory and other policies that have the effect of inducing innovation; they are limited to policies that require some governmental funding or other action but are otherwise voluntary for industry or consumers.

Table 1: Technology Policies

Direct Funding

1. R&D contracts with private firms (fully-funded or cost-shared).
2. R&D contracts and grants with universities.
3. Intramural R&D conducted in government laboratories.
4. R&D contracts with consortia that include two or more of the actors above.

Indirect Support for Technology Development; Direct or Indirect Support for Commercialization and Production

5. Patent protection.
6. R&D tax credits.
7. Tax credits or production subsidies for firms bringing new technologies to market.
8. Tax credits or rebates for purchasers of new technologies.
9. Government procurement.
10. Demonstration projects.

Information and Learning

11. Education and training (technicians, engineers, and scientists; business decisionmakers; consumers).
12. Codification and diffusion of technical knowledge (screening, interpretation, and validation of R&D results, support for databases).
13. Technical standards-setting.*
14. Technology and/or industrial extension services.
15. Publicity, persuasion, consumer information (including awards, media campaigns, etc.).

* Refers only to standards intended to ensure commonality (e.g., driving cycles for testing automobile fuel economy and/or emissions) or compatibility (e.g., connectors for charging electric vehicle batteries), not to regulatory standards.

Table 2: Policy Tools Compared (p. 1)

Policy Category	*Strengths*	*Weaknesses*	*Further Comments*
Direct Funding			
1. R&D contracts with private firms.	Proven effectiveness in mission agencies, especially defense.	In the absence of a well defined and widely accepted mission, can be hard to defend politically and to manage; may attract pork-barrel spending.	Established mechanisms, ample experience base for selection of technical objectives and evaluation of competing proposals.
2. R&D contracts and grants with universities.	Many centers of research excellence; strong competition (for funds, faculty, graduate students, etc.).	Applicable experience base smaller for applied R&D than more basic work.	Well-established agency procedures.
3. Intramural R&D conducted in government laboratories.	High levels of expertise and excellent facilities in some laboratories.	Generally poor track records in laboratories that lack strong, stable sense of mission.	Few laboratories deeply integrated into national technological infrastructure (which may, for example, slow outward or inward technology flows).
4. R&D contracts with consortia that include two or more of the actors above.	Collaboration can help define technical objectives and minimize unnecessary duplication of effort. Diffusion to participants built in.	Precompetitive consortia tend toward lowest-common-denominator R&D. Firms that compete with one another may be reluctant to contribute their best people and ideas.	Some duplication in R&D often desirable. Recent vogue for "partnerships" may have discouraged hard-headed evaluations of actual performance.
Indirect Support for Technology Development; Direct or Indirect Support for Commercialization and Production			
5. Patent protection.	Powerful incentive for innovation in some industries and technologies.	The stronger the protection, the weaker the incentives for diffusion through imitation or circumvention.	Most effective for "simple" products, such as pharmaceuticals, chemicals, and basic materials, for which composition or processing can be protected.
6. R&D tax credits.	Popular, relatively uncontroversial.	Difficult to target toward particular technologies.	Firms normally pursue R&D and commercialization for business reasons which tax credits affect little if at all; credits likely to subsidize work that would be conducted anyway.

Table 2: Policy Tools Compared (p. 2)			
7. Tax credits or production subsidies for firms bringing new technologies to market.	Well-suited, at least in principle, to targeting of particular technologies.	Subject to attack as corporate welfare and susceptible to political manipulation.	The larger the credits or subsidies, the more likely they will go to the best lobbyists rather than the best ideas.
8. Tax credits or rebates for purchasers of new technologies.	As above, but tend to pull technologies into the marketplace rather than pushing from the supply side.	As above, though less likely to attract lobbying because benefits are harder to channel to particular firms.	
9. Government procurement.	Powerful stimulus when government is a major customer.	Susceptible to political logrolling in absence of mission-imposed discipline.	
10. Demonstration projects	Can validate technologies, explore applications where market has yet to develop.	Tainted by past undertakings widely viewed as wasteful and ineffective, including energy projects in the 1970s.	Technical objectives may be compromised by need to show positive results so as to maintain political support and funding.
Information and Learning			
11. Education and training.	Powerful, pervasive mechanisms for diffusion of knowledge.	Many established channels slow-acting (e.g., university degree programs). Workforce training policies fragmented and underdeveloped compared with education.	Quality, particularly of shorter education/training courses, highly variable. Formal education and training best suited for transmission of information and knowledge widely accepted as valid, broadly useful.
12. Codification and diffusion of technical knowledge.	Expert consensus on best practices reduces technical risks and uncertainties.	With exceptions such as building codes and military standards, existing institutional settings poorly understood.	Many well-established mechanisms (reference documents, consensus best practices, computer-aided engineering methods and databases, technical review articles, etc.) fall outside traditional government purview.
13. Technical standards-setting.	Potential for deep and lasting impacts.	Consensus standards development slow; often leads to compromise among competing private interests with limited public-interest input. May lock in inferior technologies.	Special interests have powerful incentives to seek to dominate the process.
14. Technology/ industrial extension.	Can directly address knowledge gaps, misunderstandings.	Labor-intensive; costly to reach large numbers of firms or individuals.	Long-term acceptance, viability yet to be fully established, except in agriculture.
15. Publicity, persuasion, consumer information.	Possible to reach large numbers of people and organizations at relatively low cost.	Unlikely to alter vested interests or have much effect on cost-based decisions.	Competing interests may attenuate, perhaps distort, the message. Many Americans skeptical, cynical about information from government.

The listing in Tables 1 and 2 is restricted to policy tools with political legitimacy in the United States. The notion of technology policy remains somewhat inchoate and, when it seems to touch on "industrial policy," contentious. Opposition to industrial policy goes back to the founding of the republic, has roots in the opposing views of the Federalists and anti-Federalists concerning desirable pathways for economic development. Politics, in other words, delimits and conditions technology policies. Policies for industrial technology development that might meet with approval in, say, France or Japan do not necessarily pass the tests of acceptability here. While the amalgam of politics and policy has solidified for science and research, it holds for technology only when cemented by mission imperatives, as in defense. Indeed, reasonably stable public and political support are part of what it means to have a "mission."

Large-scale federal support for science and for missions other than agriculture are postwar developments. As late as 1940, the U.S. government budgeted more for agricultural research than for military R&D ($29.1 million compared with $28.6 million).[39] Military R&D rose steeply through 1945, then declined along with the rest of the defense budget in the interregnum preceding the Korean War. Nonetheless, the armed forces had learned that research and science could make major contributions to weapons systems. As early as 1944, Henry H. (Hap) Arnold, commanding general of the U.S. Army Air Forces, announced that "For twenty years the Air Force was built around pilots, pilots, and more pilots. The next twenty years is going to be built around scientists."[40]

Military R&D increased seven-fold during the 1950s, the seminal decade for both science and technology (S&T) policy and for Cold War defense policy. Fierce fighting in Korea demonstrated that national security would require more than a nuclear deterrent. To offset the millions of troops fielded by the Soviet Union, which had not demobilized after World War II, the United States would have to make heavy continuing investments in high-technology weaponry. In 1957, *Sputnik* drove home the point, showing the entire world that the Soviets had, or soon would have, the ability to target the United States with ballistic missiles.

Although most of the Pentagon's R&D dollars went for the engineering of weapons systems, funds for basic and applied research expanded too. The Department of Defense (DoD) channeled support into the physical sciences and engineering (including oceanographic research that provided baseline data on global warming), into nuclear weapons, nuclear submarines, and a nuclear-powered bomber, and into new generations of jet-propelled bombers and fighters (ten supersonic fighters alone during the 1950s, a

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[39] Federal Funds for Science XI: Fiscal Years 1961, 1962, and 1963, NSF 63-11 (Washington, DC: National Science Foundation, 1963), Table C-32, p. 136. I have included spending by the National Advisory Committee on Aeronautics in the military total.

[40] Quoted in Michael H. Gorn, Harnessing the Genie: Science and Technology Forecasting for the Air Force, 1944-1986 (Washington, DC: Office of Air Force History, 1988), pp. 17-18.

decade in which American firms designed more new military planes than in all the years since). Some of the era's technological ventures now seem heroic verging on the bizarre: $1 billion went toward the *Dyna-Soar* space plane, intended to skip along the earth's outer atmosphere (like the nuclear bomber, it was never built); the Army, not to be left behind, proposed a tank with a detachable flying turret. Along the way, means to organize and manage this explosion of technical activity had to be invented.

As the *ad hoc* structures put in place during World War II melted away, a new set grew up in their place, beginning in 1946 with the Office of Naval Research (ONR) and the Atomic Energy Commission (AEC). By 1950, the year in which Congress, after long debate, finally authorized the National Science Foundation, the United States had in place a relatively well-defined science policy. Ever since, government financing of basic research has enjoyed widespread support. Agricultural research had helped raise the incomes of farm families early in the century; science helped win World War II and would do the same in the Cold War; during the Nixon administration, Washington declared war on cancer. Widespread recognition that economic principles provided justification for public support of research came only after "science policy" had been firmly established in Washington.

By 1958, with formation of the National Aeronautics and Space Administration (NASA) and the (Defense) Advanced Research Projects Agency, the main structures of mission support for technology and science were also in place. Relatively little in these structures has changed since, even though annual R&D appropriations have increased from the range of $5 billion to that of $100 billion.

Since the close of World War II, the United States has spent $1.6 trillion (in constant 1996 dollars) on military R&D.[41] The very magnitude of this spending tends to hinder analysis and understanding. The federal government has spent another $1.9 trillion (also in 1996 dollars) on purchases of military systems and equipment. Procurement has often been a major stimulus to innovation, as for jet engines. In the early years of microelectronics, small merchant semiconductor firms, knowing that sales and profits would follow if they could produce devices meeting the needs of DoD and NASA, accounted for many technical advances, including the invention of the IC. Their innovations enabled them to capture the lion's share of sales for military and space programs. Over time, costs declined and functional performance improved, opening the way to commercial sales. Government procurement helped spawn an industry that within a few years had left its military roots behind.

"Non-technology" policies also had substantial influence. In microelectronics and computing, antitrust enforcement encouraged entry by new firms and the spread of technical knowledge. For the Internet, deregulation of telecommunications during the 1980s led competing carriers to invest in more fiber-optic trunk capacity than needed for voice communications — excess capacity fortuitously available for the rapid expansion

[41] Historical Tables, Budget of the United States Government: Fiscal Year 2003 (Washington, DC: Government Printing Office, 2002), Table 9.7, p. 171.

of data communications. Airline regulation, by barring most fare competition before the late 1970s, encouraged carriers to seek customers by flying the latest planes equipped with the latest engines, thereby speeding diffusion and learning. Decontrol of natural gas prices beginning in 1978 encouraged utilities to purchase gas turbines, which could easily burn the newly attractive fuel; government subsidies for nuclear electricity, on the other hand, exerted counter-pressures.

Technology policies cannot be viewed in isolation. They come intermingled with science policies, with economic regulation, including antitrust, and with missions such as defense and health care. These missions are malleable, but too much extension guarantees attacks by critics who believe the risks of government failure outweigh the risks of market failure. With exceptions for veterans and public health, government has rarely involved itself in the delivery of health services, even though federal, state, and local bodies pay about 45 percent of the nation's $1.3 trillion health care bill (60 percent if tax expenditures are included). Perhaps because the search for improvement in care might too easily edge off-mission, be portrayed as straying from science toward "socialized medicine," Washington has been content to direct an ever-expanding flow of funds into research, in the hope that disease cures will eventually trickle out to patients.

A Weakness in Diffusion

During the 1950s, the federal government, confident in U.S. technological and economic supremacy and in thrall to the linear model sketched by Vannevar Bush, head of the wartime Office of Scientific Research and Development (OSRD), in Science - The Endless Frontier, paid little attention to deployment of new technologies. Bush had opened his proposal for the postwar restructuring of S&T as follows:

> We all know how much the new drug, penicillin, has meant to our grievously wounded men on the grim battlefronts of this war …. Science and the great practical genius of this Nation made this achievement possible.
>
> Some of us know the vital role which radar has played …. Again, it was painstaking scientific research over many years that made radar possible.[42]

Applications, in this view, follow naturally and necessarily from research.

Students of innovation had demolished the linear model by the late 1960s.[43] Nonetheless, the image of a cornucopia of new technologies spewing from a pipeline fed by basic

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[42] Science - The Endless Frontier: A Report to the President on a Program for Postwar Scientific Research (Washington, DC: National Science Foundation, 1990 [reprint of the July 1945 original]), p. 10. Bush's encomium to the "painstaking scientific research" underlying radar was a half-truth; radio and television engineering, much of it cut-and-try, also contributed greatly. See Louis Brown, A Radar History of World War II: Technical and Military Imperatives (Bristol, UK: Institute of Physics, 1999).

[43] E.g., John Jewkes, David Sawers, and Richard Stillerman, The Sources of Invention, Second Edition (London: Macmillan, 1969); Raymond S. Isenson, "Project Hindsight: An Empirical Study of the Sources

research remains highly attractive in political Washington. If anything, its influence has grown since the 1980s with the snowball increase in the budget of the National Institutes of Health (NIH), which has $23 billion for basic and applied research in fiscal 2002, fully half of all federal research funds. Neglect of diffusion has now come to seem the outstanding weakness in the nation's S&T policies.

After World War II, other industrial economies adopted policies to foster adoption and adaptation of technologies new and old, indigenous or imported. Only at the end of the 1980s, by which time the success of Japanese firms in the design and manufacture of a wide range of consumer goods had bred near-paranoia in some U.S. circles, did Congress direct the Commerce Department to begin what is now known as the Manufacturing Extension Partnership (MEP). Agriculture, the longstanding exception to the neglect of diffusion, provided a precedent and loose model. For decades, the Department of Agriculture had budgeted for R&D and extension in proportions of about two to one. The policy, under which extension agents work directly with farmers to improve productivity, had its genesis as part of the effort to improve living standards for farm families around the turn of the century, a time of widespread rural poverty.[44]

Productive efficiency likewise provided the spur for MEP and many state-level industrial extension programs. Statistical data showed labor productivity in small U.S. manufacturing firms to be around 70 percent of that in larger firms with similar lines of business. Many of the small firms sold their output to companies such as automakers that faced stiff international competition, putting the latter at a disadvantage in terms of cost and quality (purchased parts comprise over half the content of many vehicles). A wide range of efficiency-enhancing methods, including "continuous improvement" and total quality management (TQM), had been successfully implemented in the United States by Japanese firms such as Toyota. Yet these innovations, which with many others coalesced as part of lean production, were slow to spread. It took American industry about 15 years to understand and adopt technologies that diffused more quickly not only within Japan but in third countries. The differences can be traced to institutions.[45] In Japan, broad-based industry and employer associations helped codify best practices. Large Japanese manufacturers transmitted them to suppliers, while government programs helped unaffiliated small firms. In the United States, business, trade, and professional groups, consultants, and government played relatively minor roles in untangling myth and misinformation from methods and practices of proven effectiveness.

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of Ideas Utilized in Operational Weapon Systems," Factors in the Transfer of Technology, William H. Gruber and Donald G. Marquis, eds. (Cambridge, MA: MIT Press, 1969), pp. 155-176.

[44] Roy V. Scott, The Reluctant Farmer: The Rise of Agricultural Extension to 1914 (Urbana: University of Illinois Press, 1970). On MEP, see Philip Shapira, "US Manufacturing Extension Partnerships: Technology Policy Reinvented?" Research Policy, Vol. 30, 2001, pp. 977-992.

[45] Robert E. Cole, Strategies for Learning: Small-Group Activities in American, Japanese, and Swedish Industry (Berkeley: University of California Press, 1989). Also relevant is Cole's Managing Quality Fads: How American Business Learned to Play the Quality Game (New York: Oxford University Press, 1999).

While many of the incremental innovations that became part of lean production originated in "learning-by-doing" on the factory floor, new medical practices stem primarily from research. Despite this and many other differences, the underlying productivity problem is not dissimilar. With NIH spending large sums, new knowledge issues at firehose volumes: each month the National Library of Medicine adds more than 30,000 citations to its databases. By all the evidence, this new knowledge has little immediate effect on service delivery. Neither widespread dissatisfaction with quality nor rising costs have generated responses aimed at improving routine care, even for the relatively short list of chronic conditions such as diabetes and heart disease that affect millions of Americans and account for a large fraction of morbidity and costs.[46] Competition remains localized; there has been no force for improvement comparable to the pressures on U.S. manufacturers whose customers can compare products in dealer showrooms or at Circuit City. Providers have yet to discover and implement techniques such as TQM, much less some sort of parallel to the "Toyota Production System."[47] Evaluations find continuing medical education, intended to keep the nation's 760,000 physicians up to date and informed, ineffectual.[48] Managed care seems a spent force, perhaps because most of the incentives reward short-term cost control rather than long-term improvement in health outcomes (in the long term, the cost of a given individual's care is likely be borne by other entities). Yet government remains content to support biomedical research as if applications will follow automatically.

The computer revolution provides a final illustration of the slow, piecemeal nature of technological learning. Despite rates of real cost decline for hardware that have averaged around 20 percent annually for more than half a century (unprecedented in economic history), information technology (IT) has not resulted in large observed gains in aggregate economic performance. Indeed, trends in U.S. labor productivity have been disappointing, with increases since 1973 at barely half the earlier rate (the well-known "productivity paradox").[49] While there is no consensus on the reasons, contributing factors appear to include the relatively gradual pace at which productivity-enhancing IT applications have penetrated the economy as a whole (large pockets of very intense activity notwithstanding) and the decidedly mixed success of firms that have sought to

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[46] Crossing the Quality Chasm: A New Health System for the 21st Century (Washington, DC: National Academy Press, 2001). To give a concrete example, one survey of 1600 cardiologists and internists found best-practice treatments prescribed for only 12 to 25 percent of patients diagnosed with irregular heartbeats. See Thomas M. Burton, "An HMO Checks Up On Its Doctors' Care And Is Disturbed Itself," Wall Street Journal, July 8, 1998, pp. A1, A8.

[47] To be fair, there has been discussion in health care circles of quality practices such as TQM. But levels of understanding seem shallow, much as in U.S. manufacturing around 1980.

[48] David A. Davis, Mary Ann Thomson, Andrew D. Oxman, and R. Brian Haynes, "Changing Physician Performance: A Systematic Review of the Effect of Continuing Medical Education Strategies," Journal of the American Medical Association, Vol. 274, September 6, 1995, pp. 700-705.

[49] The Bureau of Labor Statistics' series for labor productivity in the nonfarm business sector, the usual measure, showed an average annual increase of 3 percent for the period 1960-1973, but only 1.6 percent for the years 1973-2001.

restructure their internal operations to take advantage of IT. Large numbers of organizations manage to improve productive efficiency; large numbers also fail.[50] The net result appears to be a relatively slow rate of performance increase overall.

The U.S. weakness in diffusion stems from social and institutional factors that federal policies have not remedied and sometimes, as in health care, have barely recognized. While the research community argues vigorously for more money for science, there is no comparably influential constituency for diffusion (not even for workforce training), even though it is widely understood that society will only begin realize the benefits of innovation as applications become widespread.

Coordination and Management

Priorities set at high levels shape but cannot fully determine the multitude of individually small decisions through which much of S&T "policy" is implemented. These patterns too were set in the early postwar years. Vannevar Bush believed that priorities should be determined by the best and the brightest among the nation's scientists and engineers. But he also held that "Scientific administration was best managed … with responsibility weighted toward the bottom of the organization and in the hands of the men in closest touch with the projects themselves." Thus OSRD programs "were cobbled from tens of thousands of separate bargains stuck by individual scientists, entrepreneurs, and [military] officers …."[51] ONR and other agencies that followed in its wake adopted procedures much like those of OSRD. The uneasy relationship between the White House Office of Science and Technology Policy and the agencies, like that between the Department of Energy and the laboratories it inherited from the AEC, mirrors, in part, tensions between top-down policymaking and bottom-up technical judgment.

Ten agencies enjoy annual R&D appropriations exceeding $500 million; more than a dozen others get smaller sums. Neither the White House nor Congress can routinely tell them what to do and expect them to do it (after all, for many projects and programs only experts in the relevant discipline or subdiscipline can claim full understanding of what is being funded and why). There is no overall federal R&D budget; analysts have a hard time simply tracking flows of funds. More than 700 federal laboratories — so many that it took a census by the General Accounting Office to pin down the total — absorb, almost

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[50] We discuss the reasons in "Technology and Industrial Performance in the Service Sector: Field Research Report," December 1997, and "Technology and Industrial Performance in the Service Sector: Final Comparative Assessment," January 1998, Keystone Research Center, Harrisburg, PA, for the Technology Administration, U.S. Department of Commerce.

[51] Larry Owens, "The Counterproductive Management of Science in the Second World War: Vannevar Bush and the Office of Scientific Research and Development," Business History Review, Vol. 68, 1994, pp. 515-576; quotations from pp. 529 and 537. Owens argues that in relying so heavily on day-to-day decision-making at working levels, Bush set in motion forces that ultimately undermined his elitist strategy for reshaping postwar S&T policy.

unnoticed, a greater share of federal R&D dollars today than two decades ago.[52] Big projects get attention — missile defense, the $30 billion international space station, genome mapping. But to a considerable extent, S&T policy reduces to what the agencies do, which in turn reduces mostly to what they have always done. NIH funds research because that has been its mission since the 1930s. DoD buys high-technology weapons in profusion because that helped win the Cold War. An entrenched lobby and nostalgia for a vanishing way of life keep agricultural extension going in an urbanized nation in which agribusiness firms, rather than extension agents, tell contract farmers how to raise their chickens.

It is tempting to suggest that decentralization in S&T has devolved into incoherence and disarray. That would risk mistaking a source of strength for one of weakness. Certainly the United States bears considerable costs through fragmentation and lack of coordination among the many policies that affect innovation. The situation is especially bad in defense, where inter- and intra-service rivalries — fighters versus bombers for the Air Force, submarines versus aircraft carriers for the Navy — chew up resources and render long-range planning close to irrelevant, as the armed forces strive to preempt civilian authorities by presenting multi-billion dollar acquisition decisions as *faits accomplis*. Yet if duplication and waste seem almost everywhere, competition for resources contributes much to the vitality, flexibility, and dynamism so evident in the nation's innovation system, a system that has generated not only the unmatched military capabilities on display in the Persian Gulf in 1991 and more recently in Afghanistan, but an array of spinoffs and spillovers such as the Internet that continues to surprise those who were ready, in the 1980s, to proclaim the U.S. model exhausted and Japan poised to move ahead technologically and economically.

In a study that stresses the extent to which government's contributions to computing technologies were unplanned and unanticipated, a National Research Council committee observed that:

> Research … is a highly unpredictable endeavor. [The] most important contributions often differ from those originally envisioned.
>
> Projects that appear to have failed often make significant contributions to later technology development or achieve other objectives ….[53]

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[52] Seventeen federal agencies operate or support 500-plus laboratories, including those managed by contractors. Some of the laboratories have multiple facilities, for a total of more than 700 "campuses." Science & Engineering Indicators - 1998 (Arlington, VA: National Science Board/National Science Foundation, 1998), pp. 4-26 and A-164 and Appendix table 2-6, pp. A-22-23. One-third of federal R&D went to the federal laboratory system in 1980, nearly two-fifths (39 percent) in 1998.

[53] Funding a Revolution: Government Support for Computing Research (Washington, DC: National Academy Press, 1999), pp. 11 and 5.

Much earlier, in the context of the near-panic caused by *Sputnik*, which had led to outraged demands in Washington for "stronger management" and "tighter coordination," Charles J. Hitch and Roland N. McKean argued that:

> These criticisms … treat as certain what is highly uncertain. They try to strengthen control at the top when what is needed is initiative and spontaneity at the bottom. They try to suppress competition and diversification because particular duplications are obviously wasteful from the vantage point of hindsight, apparently unaware that … competition is our best protection against bureaucratic inertia.[54]

The point is not to excuse sloppy management or outmoded policies. Rather, it is to highlight the unknowns that are part and parcel of innovation.

Congress and the public have mostly tolerated the high costs and high risks that accompany high technology in defense, notwithstanding periodic bursts of criticism sparked by revelations of $2000 coffee-makers or program-level mismanagement of the sort that led to the 1991 cancellation of the Navy's A-12 attack plane. Congress and the public likewise seem to understand that basic research is a hit-or-miss proposition, that years of painstaking work sometimes end in box canyons of irrelevancy or error rather than the "breakthroughs" funding agencies like to tout. At a remove from defense or science, tolerance diminishes. Yet "mistakes" are part of the price for the social benefits of innovation. Too few failures in technology programs and policies suggest that risks have been avoided rather than accepted.

Conclusion

Pathbreaking innovations are rare and unpredictable. Yet even the most radical, the microprocessor and the Internet no less than the gas turbine, depend for their economic impacts on lengthy sequences of incremental improvement. Support for incremental innovation thus supports radical innovation. There is one major proviso: government policy cannot lock development into particular pathways. Policies must encourage the technological equivalent of ecological diversity through support for competing ideas. The corollary: agencies too should compete, within limits, to ensure that alternative, indeed divergent, paths will be pursued.

Technology policy must also reach farther beyond the reflexive focus on R&D. Even today, innovations do not necessarily begin in science or research. Some, such as the microprocessor, originate in "non-R&D" technical work. Others, such as lean production in the auto industry, incorporate numerous undocumented contributions by "unskilled" employees. Nonetheless, R&D often becomes the first and only choice of policymakers because familiar, accepted, politically safe. The habitual focus on R&D contributes to lack of attention to diffusion and learning, which tend to be protracted even in the

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[54] The Economics of Defense in the Nuclear Age (Cambridge, MA: Harvard University Press, 1960), p. 256.

presence of strong economic forces. When such forces are lacking, as in health care, even very large expenditures on research may have little effect in attaining objectives of immediate social concern.

Chapter 3: Valleys of Death and Darwinian Seas: Financing the Invention to Innovation Transition in the United States

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The basic science and technology research enterprise of the U.S.—sources of funding, performing institutions, and researcher incentives and motivations—is reasonably well understood by academics and policy makers alike. Similarly corporate motivations, governance, finance, strategy, and competitive advantage have been much studied and are relatively well understood. But the process by which a technical idea of possible commercial value is converted into one or more commercially successful products, i.e. the transition from invention to innovation, is highly complex, poorly documented, and little studied. This paper asks: How is basic research converted into successful commercial innovations? Are there financial, institutional or entrepreneurial "gaps" that increase the risks and costs of radical, technology-based innovations? What is the role of governments, both federal and state or provincial, in promoting the commercial transition from an invention to an innovation? What lessons can be learned from the experience of the Advanced Technology Program (ATP) of the United States Department of Commerce, one of the few Federal programs specifically intended to meet this need?

Virtually all economic growth in the U.S. economy, and indeed all industrial economies, comes from incremental improvements in existing products and processes. These incremental improvements are motivated by market pressures on firms to either improve product performance, reduce cost of production, or both. In the U.S. they are financed almost entirely by private investment. In the last decade total national R&D investment has risen to over $250 billion annually, supporting a Gross National Product of $10,253 billion in year 2000. Real increases in U.S. national R&D have all come from industry, increasingly focused on near term product development. Government funding for R&D has been approximately flat in inflation-adjusted dollars.[55]

As the pace of technical advance quickens and product cycles compress, established corporations are increasingly pressured to seek opportunities for such incremental technological change.[56] However, incremental technical change alone is not adequate to ensure sustained growth and economic security. Sustained growth can occur only with the continuous introduction of truly new goods and services—radical technological innovations that disrupt markets and create new industries.[57] Radical technological change, in turn, is a function of the capacity to turn science-based "inventions" into commercially viable "innovations." As Weitzman (1998: 333) has noted, "the ultimate limits to growth may lie not as much in our ability to generate new ideas, so much as in our ability to process an abundance of potentially new seed ideas into usable forms."

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[55] Data from the Bureau of Economic Analysis, <www.bea.gov/briefrm/tables/ebr1.htm>.
[56] Branscomb and Auerswald (2002), Annex I.
[57] See argument and evidence in Lucas (1988, 1993).

Definition of terms: We use "invention" as shorthand for a commercially promising product or service idea, based on new science or technology, that is protectable but not necessarily by patents or copyrights. By "innovation" we mean successful entry into a market of a new science or technology-based product, i.e. commercialization of an "invention." By early stage technology development (ESTD) we mean the technical and business activities that transform a commercially promising "invention" into a business plan that can attract enough investment to enter a market successfully, and through that investment become a successful innovation. This requires reducing the needed technology to practice, defining a production process with predictable product costs and relating the resultant product specifications to a defined market.

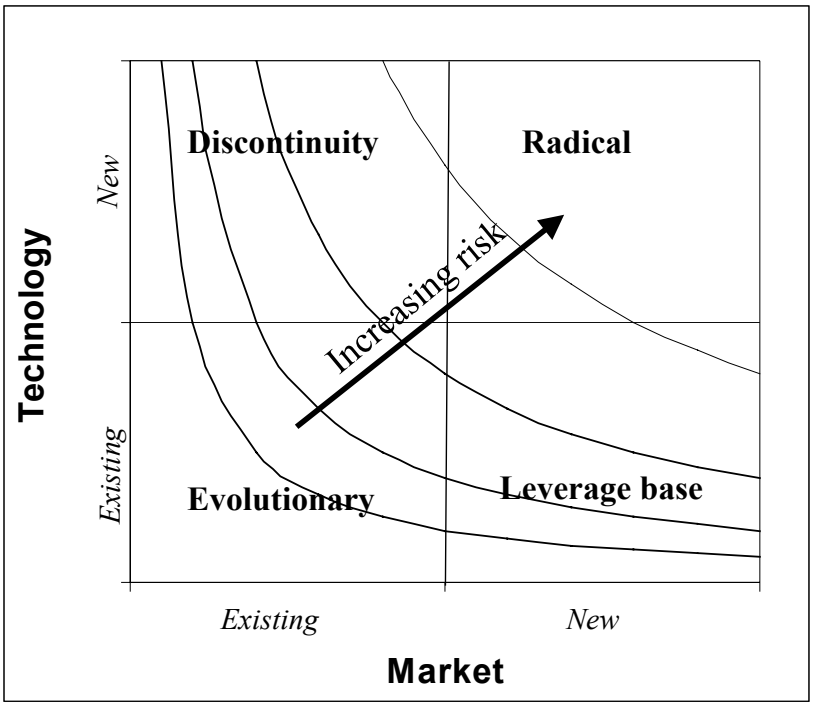

Figure 1. Market and technology risk. The solid lines represent constant overall risk. *Source:* Hartman and Myers (2001).

Understanding the invention to innovation transition is essential in the formulation of both public policies and private business strategies designed to more efficiently convert the nation's research assets into economic assets.

Policy analyses and political debates relating to R&D appropriations frequently involve inferences about economic outcomes from the aggregate investment of $60 billion in non-defense, publicly funded R&D.[58] The Congress is aware that analyses at this high level of aggregation do not allow quantitative evaluation of the relationship between the

[58] Data from the American Association for the Advanment of Science, <www.aaas.org/spp/dspp/rd/trtot03p.pdf>.

policies under which these investments are made and the economic and social outcomes they produce. It was for this reason that the Government Performance and Reports Act—covering not only R&D programs, but all Federal government programs—was passed in 1993.[59] In the context of that act, every agency that funds research is required to document in its budget submissions, not only "outputs" (measured in terms of in publications, patents and training) but also outcomes and impacts in broader economic and social terms. Agencies have found this requirement difficult to satisfy.

The result is that federal S&T policy, as it relates to the expectation of economic outcomes, still depends on the following principles and policies:

- A residue of confidence in the "social contract for science" that takes as a matter of faith that while the outcomes from science are difficult if not impossible to predict, experience shows that viewed in hindsight they dramatically exceed their public costs.[60]
- Statutes intended to increase the incentives for commercializing government funded science (technology "pull" policies) of which the most significant was the 1980 Bayh-Dole Act, allowing universities and other contractors and grantees to own patents issued from government-funded research.[61]
- A larger number of statutes which can be characterized as technology "push" polices, intended to encourage the transfer of government research to commercial enterprises. These include the Stevenson-Wydler Act and its amendments, for example encouraging Cooperative Research and Development Agreements (CRADAs).
- Two statutes intended to create government investments in research to create technologies of high commercial promise. These include the Small Business Innovation Research program and the Advanced Technology Program (ATP) both managed by the National Institute of Standards and Technology (NIST) in the U.S. Department of Commerce.

[59] Data from the Office of Management and Budget <www.whitehouse.gov/omb/mgmt-gpra>.
[60] This idea was articulated in Vannevar Bush's *Science the Endless Frontier* published in 1945 as a report to President Truman. In return for generous public investments in research, scientists committed to a highly creative, competitive, and honest performance.
[61] Our use of the phrases "technology push" and "technology pull" is idiosyncratic, and not intended to parallel the terms "supply push" and "demand pull" as widely employed in the literature on induced innovation, including by Mowery and Norberg-Bohm in this volume. In the context of that complementary literature, both sets of statutes to which we refer would be considered "supply push" policies. See also Ruttan (2000).

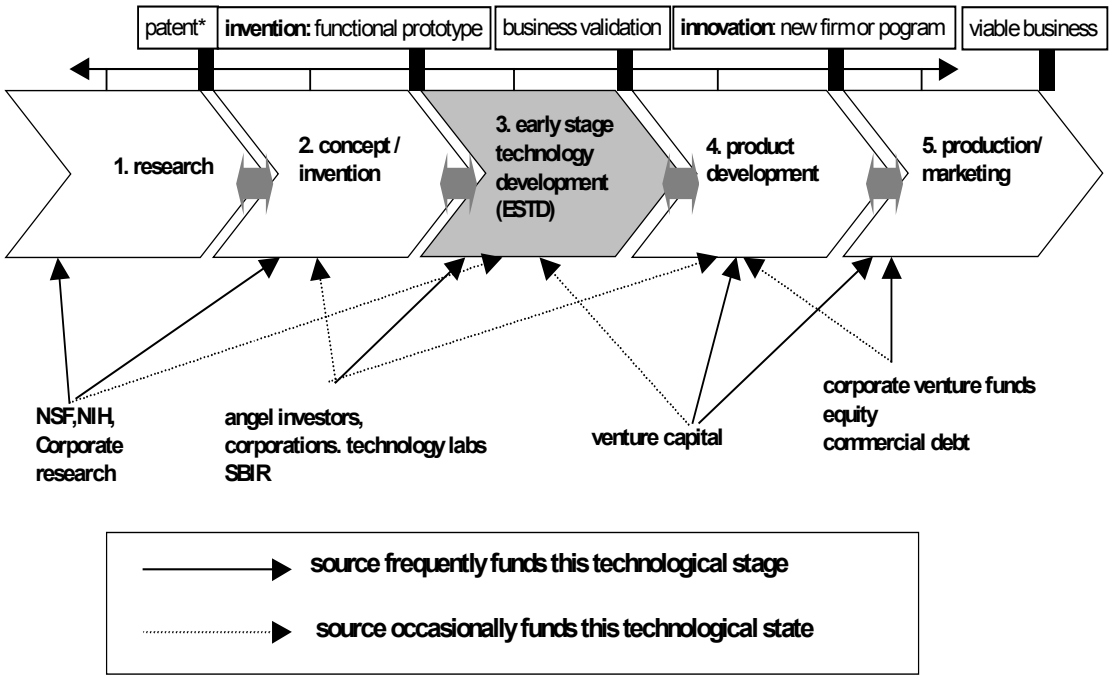

Figure 2. Sequential model of development and funding
The region corresponding to early stage technology development is stage 3, shaded in gray.
The boxes at top indicate milestones in the development of a science-based innovation.
The arrows across the top of, and in between, the five stages represented in this sequential model are intended to suggest the many complex ways in which the stages interrelate. Multiple exit options are available to technology entrepreneurs at different stages in this branching sequence of events.
* A more complete model would address the fact that patents occur throughout the process.

With the exception of ATP, none of these statutes was justified by a detailed model of how government-funded advanced research results in high-tech innovations. ATP attempts to invest in that process directly, and it has been highly controversial politically from the time of its passage in 1988. What, then, do we know about how radical, technology-based innovations come about? What can governments do to foster such innovations? Is ATP an effective policy tool for this purpose, or it is merely "corporate welfare" as its critics claim?

In order to answer these questions we first analyze the processes that relate publicly funded research to successful market entry of new products or processes, i.e. to innovations.[62] This analysis emphasizes disjunctures in the innovation process of

[62] An innovation is a product or process, new to the enterprise, that is successfully introduced into commerce. The adjective 'innovative' simply means clever, novel, and perhaps commercially promising. An innovative idea is not an innovation, at least not until it is successfully produced and sold.

relevance to public policy. We then report findings from our research over the past two years concerning the sources of funding for such "early stage" technology development. We conclude by describing implications for public policy, focusing on the lessons learned from a decade of experience with the Advanced Technology Program.

The Invention to Innovation Transition

A diagram of the innovation process that allows us to define the "invention to innovation" transition is presented in Figure 2.[63] The arrows across the top and in between the five stages of technology development and funding are intended to suggest the many complex ways in which the stages interrelate. [64] Figure 2 identifies the stages of activity, starting with research (phase 1) leading to a technical concept of commercial value that is protected, perhaps by a patent (phase 2). Phase 3 is the most critical phase in the transition from invention to innovation. This is the point at which the technology is reduced to industrial practice, a production process is defined from which costs can be estimated, and a market appropriate to the demonstrated performance specifications is identified and quantified. *We are referring to phase three (shaded) when we employ the phrase "early stage technology development" (ESTD), as defined in the box at the opening of this chapter.* When ESTD work is completed, product development (phase 4) begins. A pilot line is produced and the enterprise is ready to enter the market. At this point an innovation is achieved, and in phase 5 the product enters the market and customers provide initial feedback for product development and a business is created which is ready to be financed or perhaps acquired.

The first two phases lie in the domain of the research enterprise; and may be publicly funded. The technical entrepreneurs who create the concept in phase 2 may have little business experience, but they may have high commitment to their technical vision. The venture capital industry, always looking for opportunities to invest where the returns may by high enough to justify the business risks are unlikely to take the opportunity seriously until phase 5 is reached. In some cases they will invest, in an exploratory fashion, in phase 4.

The specific region of the innovation space that we are most interested in is bounded at the earliest stage with the verification of a commercial concept through laboratory work and extends through the identification of what looks like an appropriate market.

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[63] The literature on technology management contains innumerable variants on this diagram. A good example is that developed in Lane (1999). Formal models involving staged technology development include Aghion et al. (1999) and Judd (2002).

[64] Reporting on their interviews of corporate technology managers and venture capitalists, the team from Booz Allen Hamilton emphasized the importance of interpreting the framework presented in Figure 1 as a sequence of idealized stages potentially linked in complex ways: "Most interviewees generally agreed with the classification of R&D into the four steps in the innovation framework used in our discussions (Basic, Concept/Invention, ESTD, Product Development). However, there were many reactions to the linear simplicity of the framework, compared to the typical path from invention to commercial innovation that the participants have experienced. The four step framework represents an idealized view of technology progression, while the actual pathway included multiple parallel streams, iterative loops through the stages, and linkages to developments outside the core of any single company."

Congressman Vern Ehlers, among others, uses the term "Valley of Death" to dramatize the particular challenges facing entrepreneurs engaged in the transition from invention to innovation. This term reinforces the "capital gap" perspective on early stage innovation: champions of early stage projects must overcome a shortfall of resources.[65]

The imagery of the Valley of Death (which connotes Death Valley in Nevada, USA) leads to the cartoon drawn by Congressman Ehlers in Figure 3a. Death Valley suggests a barren territory when, in reality, between the stable shores of the S&T enterprise and the business and finance enterprise is a sea of life and death, of business and technical ideas, of 'big fish" and little fish contending, with survival going to the creative, the agile, the persistent. Thus we propose an alternative image: the Darwinian Sea (Fig. 3b).

Institutional and Behavioral Disjunctures: An Innovation Gap?

In Branscomb and Auerswald (2001) we identified the five challenges of the "Darwinian Sea" in the following terms:

- *Differing motivations for research.* Initially an innovator demonstrates *to his or her own satisfaction* that a given scientific or technical breakthrough could form the basis for a commercial product (proof of principle). However, a substantial amount of difficult and potentially costly research (sometimes many years' worth) will be needed before the envisioned product is transformed into a commercial reality with sufficient function, low enough cost, high enough quality, and sufficient market appeal to survive competition in the marketplace. Few scientists engaged in academic research (or the agencies funding their work) have the necessary incentives or motivation to undertake this phase of the reduction-to-practice research.
- *Disjuncture between technologist and business manager.* On each side of the Darwinian Sea stands a quite different archetypal character: the technologist on one side, and the investor/manager on the other. Each has different training, expectations, information sources, and modes of expression. The technologist knows what is scientifically interesting, technically feasible, and fundamentally novel in the proposed approach. In the event of failure, the technologist risks a loss of reputation, as well as foregone pecuniary returns. The technologist is deeply invested in a vision of what could be. The investor/manager knows about the process of bringing new products to market, but may have to trust the technologist when it comes to the technical particulars of the project in question. What the investor/manager is

[65] Entrepreneurs in many settings also report a particular difficulty in raising funds in the range of $200,000 to $2 million. The hypothesis of such a "capital gap" in seed stage funding for new ventures is discussed by Sohl (1999), and consistently supported by practitioners (see. e.g. comments by participants at a Senate Small Business Committee Forum, <www.senate.gov/~sbc/hearings/internet.html>. The hypothesis is not restricted to the United States. In 1999 the U.K. Department of Trade and Industry published a report titled "Addressing the SME [small and medium enterprise] Equity Gap." At a recent National Science Foundation sponsored conference, Jian Gao of Tsinghua University (Beijing, PRC) reported that an analogous "capital gap" phenomenon has been observed to exist in China. See also Preston (1993) and Chertow (2001).

Figure 3a. The "Valley of Death" image, as drawn by Congressman Vern Ehlers.

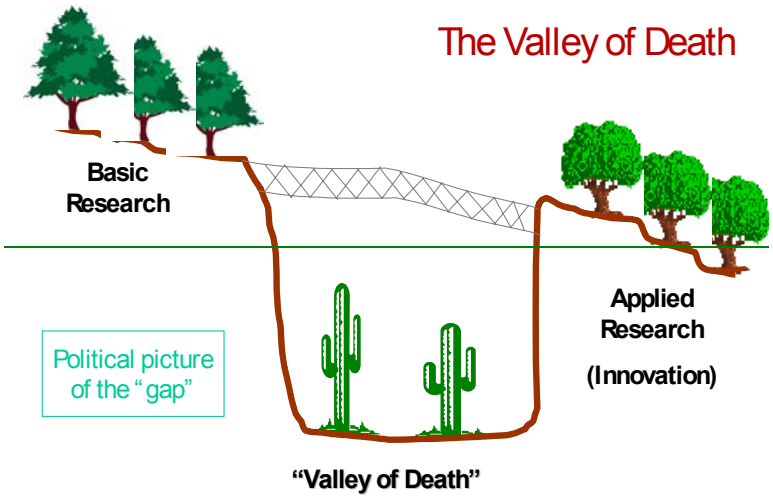

Figure 3b. An alternative metaphor for the invention to innovation transition: the "Darwinian Sea."

generally putting at risk is other people's money. The investor is deeply committed to producing a profitable return on his investment, independent of the technology or market through which it is realized. To the extent that the technologist and the investor/manager do not fully trust one another or cannot communicate effectively, the Darwinian Sea between invention and innovation becomes deeper still.

- *Sources of financing*. Research funds are available (typically from corporate research, government agencies, or more rarely, personal assets) to support the creation of the idea and the initial demonstration that it works. Investment funds can be found to turn an idea into a market-ready prototype, supported by a validated business case. In between, however, there are typically few sources of funding available to aspiring

innovators seeking to bridge this "break" in funding sources. They include "angel" investors (wealthy individuals, often personally experienced in creating new companies and/or developing new products); established firms making equity investments in high-tech startups to get a look at emergent technologies; venture capital firms specialized in early stage or "seed" investments; military or other public procurement; State or Federal government programs specifically designed for the purpose; and university funding from public or private sources.

- *Infrastructure.* Another critical obstacle typically facing champions of early stage technology development projects is the absence of the necessary infrastructure. By infrastructure we mean not only the large scale infrastructure required for final products in the marketplace (e.g., gas stations for internal combustion automobiles, or software to run on a new operating system), but also all of the "complementary assets" that may be required for market acceptance—suppliers of new kinds of components or materials, new forms of distribution and service, training in the use of the new technology, auxiliary products and software to broaden market scope.[66]
- *Creating value*. Even where a technology has demonstrated promise to create value for consumers, the question remains: how much of that value will the innovative firm be able to capture? Understanding the mechanism by which value will not only be created, but also captured, is a necessary component of the business system that allows an invention to become a successful commercial innovation. Gerald Adolph, a senior vice president in the technology consulting firm of Booz Allen & Hamilton, comments:

> We argue that value isn't created until you get a business system [model] along with the invention. The business system is the mechanism by which value is delivered to someone and captured by someone ... focusing on the business system allows you to be more articulate to those who are asking about the business implications, the success implications, the competitive implications, without requiring answer to the other questions that perhaps no one can answer at those early stages — as in, exactly how big will it be? How much will I charge for it? How much money will I make?[67]

In order to execute the given strategy for value capture, the firm in question must have the internal capabilities and other resources necessary to leverage its first mover advantage into longer term market success. At every stage, firms weigh opportunities for value creation and value capture against risks and anticipated costs. All things being equal, a large corporation will develop a given technology platform first in markets where mechanisms for value capture are better established and production costs are lower.[68] In addition to all the disjunctures between inventor and investor, there are a daunting set of external obstacles to realizing a successful venture,

[66] Teece (1987).
[67] Quoted in Branscomb and Auerswald (2002).
[68] Kolasky (2002).

difficulties that may also be viewed differently by the various parties involved in the process.

The multiple challenges that confront technology entrepreneurs seeking to traverse the "Darwinian Sea" have led some to argue a persistent "innovation gap" may exist even in the countries with relatively strong and productive innovation systems.[69] Former Undersecretary of Commerce Mary Good remarked in 1997 that "as the competitive pressures of the global marketplace have forced American firms to move more of their R&D into shorter term product and process improvements, an 'innovation gap' has developed.… Sit down with a group of venture capitalists. The funding for higher risk ventures … is extraordinarily difficult to come by."[70]

The existence of the sort of "innovation gap" postulated by former Undersecretary Good and others[71] is controversial. Skeptics point out that the part of the financial system specialized in investing in high risk new enterprises—the venture capital industry—grew dramatically in the last decade, even when the recent downturn is taken into consideration. Venture capital funds disbursed to firms reached a peak of over $100 billion in the year 2000, before dropping off to $37 billion in 2001. Interpretations vary. The White House has recently justified reductions in support to the Commerce Department's Advanced Technology Program with the statement that "the overall growth in venture capital suggests private funding is available for high-technology projects." In contrast, technology business leader Bill Joy of Sun Microsystems observed in July of 2001 that "a couple of years ago, even the bad ideas were getting capital. Now we have gone too far in the opposite direction, shutting down investment in good ideas."[72] Entrepreneurs report a dearth of sources of funding for technology projects that no longer count as basic research but are not yet far enough along to form the basis for a business plan. At the same time, venture capital firms and other investors are sitting on record volumes of undisbursed cash, with over $70 billion currently idling in funds raised during the boom years.

It is not surprising that technology entrepreneurs experience an apparent shortage of funding while undisbursed cash sits idle. Whether or not efficient markets exist on Wall

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[69] The term "gap" in this context is connotes a disjuncture rather than a shortfall of resources. Arrow (1962) and Zeckhauser (1996) set forth the theoretical basis for this point of view. Auerswald and Branscomb (2002) and Hall (2002) elaborate.

[70] Testimony before the U.S. Senate Governmental Affairs Committee. Quoted in Gompers and Lerner (1999: 2). These authors quite accurately point out an apparent contradiction in the quote from Dr. Good, which appears in its edited form to suggest that venture capitalists are reluctant to provide risk capital. Of course, this is not the case. As Gomper and Lerner describe, the venture capital mode of finance is precisely that which is specialized in providing finance in contexts where uncertainty is high and information asymmetries severe. At the same time, however, as Morgenthaler (2000) and other venture capitalists report, the risk/reward ratio for seed stage, technology based ventures is not as attractive to venture capital firms as that for slightly later stage ventures. For further discussion see Branscomb and Auerswald (2002).

[71] See also Preston (1993, 1997), Chertow (2001), Hall (2002), and the Introduction to the February 2002 report from the Secretary of Commerce titled "The Advanced Technology Program: Reform with a Purpose."

[72] *Businessweek,* July 2001.

Street may be an open question. However, efficient markets do not exist for allocating risk capital to early stage technology ventures. One often cited reason for such inefficiency concerns fundamental limits on the ability of investors in early stage technology ventures to fully appropriate returns from their investments. We focus on a second reason: serious inadequacies in information available to both entrepreneurs and investor. Early stage development involves not only high quantifiable risks, but also daunting uncertainties. When the uncertainties are primarily technical, investors are ill-equipped to quantify them. For new technologies that have the potential to create new product categories, market uncertainties are also high and similarly difficult to quantify. The "due diligence" that investors in venture capital funds require of managing partners and that angel investors require of themselves is intrinsically difficult—and getting more so as both technologies and markets become increasingly complex.

Up to a decade is required for the transition from invention to innovation. Given technical and market uncertainties, venture capitalists, angels, and bankers prefer to wait to see the business case for a new technology rather than funding speculation. The technical content of the business proposal must be sufficiently well established to provide reliable estimates of product cost, performance, and reliability in the context of an identified market that can be entered in a reasonable length of time. It is the funding of this technical bridge—from invention to innovation—that is the basis for the notion of an "innovation gap."

Sources of Funding for the Invention to Innovation Transition[73]

Who funds early stage technology development—the invention to innovation transition? Our research over the past two years involving a combination of data analysis and interviews indicates that most funding for technology development in the phase between invention and innovation comes from individual private equity "angel" investors, corporations, and the Federal Government—not, as widely believed, from venture capitalists.

Some numbers regarding technology entrepreneurship place the role of venture capital in context. In 1998, for example—probably a more reliable benchmark of innovation funding activities than 2000 when markets where at their historic peaks—the Small Business Administration reports that more than six hundred thousand new firms (with employees) were founded. That year approximately 450,000 individuals described themselves as technology entrepreneurs.[74] About 10% of those entrepreneurs, involved in approximately 20,000 start up firms, received roughly $20 billion in funding from Angel investors.[75] In contrast, only about 300 companies received "seed stage" funding from

[73] This section summarizes findings from Branscomb and Auerswald (2002).
[74] U.S. National Panel Survey of Business Start-ups, preliminary results.
[75] Estimate from Jeff Sohl, University of New Hampshire.

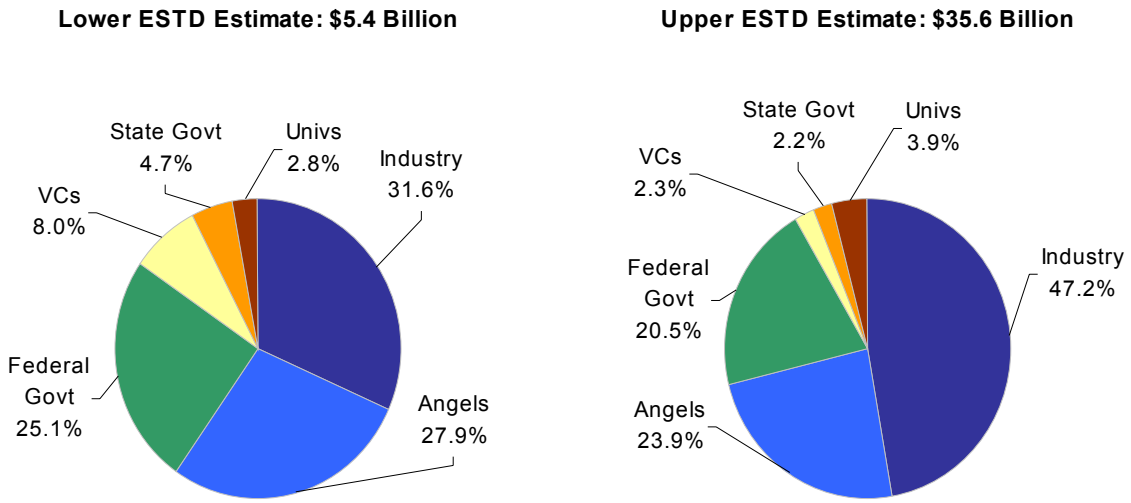

Figure 4. Estimated distribution of ESTD funding, based on narrow (lower estimate) and broader (upper estimate) definitional criteria.

venture capitalists; slightly more than a thousand firms received first time venture funding in all categories. [76]

Overall, of $266 billion that was spent on national R&D by various sources in the U.S. in 1998, substantially less than 14% flowed into early stage technology development activities. The exact figure is elusive, because public financial reporting is not required for these investments. Our method of arriving at a reliable estimate was to create two models based on different interpretations of our "early stage technology development" definition—one very restrictive (i.e. biased toward a low estimate) and the other quite inclusive (i.e. biased toward a high estimate). With this approach we conclude that between $5 billion (2%) and $36 billion (14%) of overall R&D spending in 1998 was devoted to early stage technology development. The balance supported either basic research or applied research, engineering and testing.

Although the range between our lower and upper estimates differs by several billions of dollars, the proportional distribution across the main sources of funding for early stage technology development activities is surprisingly similar regardless of whether we employ restrictive or inclusive models. Given either model, expenditures on early stage technology development by angel investors, the federal government, and large corporations funding "out-of-the-core business" technology development are comparable in magnitude. (See Figure 4.) Early stage technology development funds from each of these sources greatly exceed those from state programs, university expenditures, and the small part of venture capital investment that goes to support early stage technology

[76] Venture Economics and the National Venture Capital Association. It is also interesting to note that, according to the data gathered by the Association of University Technology Managers, only approximately 260 firms were created from university license or intellectual property.

projects. Notably—even excluding as we do the impact of government procurement—the federal role in this process is substantial: in our estimates roughly 20-25% of the total early stage technology development comes from federal sources.

As noted earlier, investments by corporations in advancing established product and process technologies to better serve existing markets comprise a dominant source of national R&D spending. But, as Booz Allen & Hamilton (2002) report, corporate technology entrepreneurs who create an innovative idea lying outside their firm's core competence and interest face risks and financial challenges similar to those faced by the CEOs of newly created firms. While corporations will indeed spend lavishly on technological innovations that support their core businesses, they are systematically disinclined to support technological innovations that challenge existing lines of business, require a fundamental shift of business model, or depend on the creation of new complementary infrastructure.

Venture capital firms are critical financial intermediaries supporting new high-growth firms. Why, then, is the role of the venture capital industry in funding early stage technology development not dominant? Popular press accounts notwithstanding, venture capital firms are not in the R&D business. Rather, they are in the financial business. Their fiduciary responsibility is to earn maximal returns for their investors. They do this through a complex set of activities that can be summarized as buying firms low and selling them high. Venture capitalists do indeed back high-growth, new ventures. In many cases, though not the majority, they support firms that are bringing radical new technologies to market. However, even when venture capitalists do support technology-based enterprises, they prefer to support firms that have at least proceeded beyond the product development stage, i.e. firms that have completed the early stage technology development which is the focus of this study. As the median size of venture capital deals has increased and the pressure to provide attractive returns to investors in mammoth funds has intensified, venture capital has tended increasingly to flow to projects in later stages of development and to already-proven technologies. For all of the above reasons, trends in venture capital disbursements should not be confused with trends in the funding of early stage technology development.

Institutional Evolution

Despite (or in response to) market inefficiencies, many institutional arrangements have developed for funding early stage technology development. This suggests that funding mechanisms evolve to match the incentives and motivations of entrepreneur and investors alike.

Champions of early stage technology projects make use of a wide variety of funding options to keep their projects alive. These include not only successive rounds of equity offerings, but also contract work, income from licensing patents, the sale of spin-off firms, and old-fashioned cost-cutting. While each of these options has its own costs and benefits, entrepreneurs do not play favorites among them when it comes to keeping their projects moving forward.

In contrast to institutional sources of equity and debt capital for advancing existing businesses incrementally, the transition from invention to innovation is financed by a great variety of mechanisms, with new ones being created every day: angel networks and funds, angel investments backed by bank debt, university and corporate equity investments, seed investments by university and corporate venture capital programs, and certain experimental R&D programs run by Federal and State agencies.

A report from the National Commission on Entrepreneurship (Zacharakis et al. 1999: 33)[77] notes that "the substantial amount of funding provided through informal channels, orders of magnitude greater than provided by formal venture capital investments and heretofore unknown and unappreciated, suggests some mechanisms for filling the gap may have developed without recognition." Yet the proliferation of institutional types is as much an indication of the particular informational challenges and structural disjunctures that define the "innovation gap" as it is one of a resolution to the challenge.

Regional and Sectoral Concentration of Resources

While our research to date has not generally focused on funding patterns at the regional and industry sector level, some important trends are apparent. First, the geographical distribution of early stage technology development activity mirrors that of innovation-related activity in general. In particular, early stage technology development is concentrated in geographical regions that invest heavily in R&D, possess developed risk-capital networks and related complementary infrastructure (e.g. specialized law firms, other suppliers), and otherwise benefit from strong university-industry linkages.

Second, angel investors provide the most significant source of early stage technology development funding for individual technology entrepreneurs and small technology startups. Since angel investors make the vast majority of their investments close to home, early stage technology development activities, particularly those of smaller firms, are likely to be concentrated in regions with active communities of tech-savvy angels.

Third, although state governments provide a relatively small portion of total early stage technology development funding, they play a critical role in establishing regional environments that help bridge the invention to innovation gap. State governments facilitate university-industry partnerships, leverage Federal academic research funds by providing both general and targeted grants, build a technically educated workforce through support of public colleges and universities, and ease regulatory burdens to create a fertile ground for technology startups. While Route 128 and Silicon Valley arose with little local or state level political support (in part because they developed the needed networks, stimulated by defense funding, in the 1950s), a number of states have created many of the features needed for successful innovation, for example, Research Triangle Park in North Carolina, which was conceived and initiated by Governor Luther Hodges.

[77] Full text available at <http://www.ncoe.org/research/RE-018.pdf>.

Fourth, we found that inter-industry differences in R&D investments are related to industry lifecycles. More mature industries, such as the automotive industry, tend to invest a smaller percentage of R&D into earlier stage technology development than less mature industries such as biotech. Booz Allen & Hamilton (2002) estimate overall corporate spending on early stage technology development to be approximately $13 billion annually, or 9% of total corporate R&D spending. The inter-industry distribution was estimated as follows: chemicals 33%; biopharmaceutical 13%; electronics 11%; equipment 10%; telecommunications 10%; basic industries 7%; automotive 3%; and computer software 0%. Spending thus was found to differ widely by industry, as well as by company within specific industries.

The entrepreneurship challenge involves the capabilities of the individual innovators who seek to carry their idea across the Darwinian Sea and participate in the fruits of a successful innovation. The rare individual—a talented business leader with a strong technical background—is able to bridge the Sea personally. A community with strong social capital may offer mentors—usually in the form of angel investors—who have been successful at commercial innovation and serve both as mentors to new technology-based entrepreneurs and as seed investors in their ideas. A key feature of these networks of innovation is that they are geographically confined to specific locations. Angels rarely invest in a firm more than an hour's drive away; a similar effect is found in seed stage venture firms.

Attesting to the localized economic development impact of strong university research, more than 80 percent of the start-up companies were located in the academic institution's home state or province.[78] In FY 2000, more than $1.26 billion in royalties were collected by U.S. colleges and universities. In addition, the *FY 2000 Annual AUTM Licensing Survey* reported 347 new products were introduced to the market and at least 454 spin-off companies were created by these institutions. inventors filed for more than 8,500 U.S. patents.[79] Universities are not only the source of many of the commercially attractive technical discoveries; they constitute a web of capabilities—technical, legal, business management, and application skills-that form the core of the social capital in areas like Silicon Valley California and Route 128 Boston.

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[78] Two-thirds of the 4,346 new licenses/options in FY 2000 were granted to companies with fewer than 500 employees. Start-up businesses were launched to commercialize 626 of the licenses. New licenses rose 11 percent over 1999 survey results. Invention disclosures rose 6 percent from 1999 to a FY 2000 total of 13,032. Patent applications grew by 15 percent from the 1999 total of 5,545 to 6,375 in FY 2000. Patents issued rose 3 percent in FY 2000 to 3,764. FY 2002 saw academic institutions taking an equity interest in 372 deals, 53 percent more than the previous year. The institutions held equity interest in 56 percent of the 454 spin-offs created in FY 2000. Over the ten years AUTM has conducted the survey, nearly 3,400 new businesses have been launched from academic research results. One hundred eighty-four institutions reported 2,309 start-ups were still independent, operating businesses at the end of 2000. The number of license/options reporting income in FY 2000 rose 8 percent from 1999. Total adjusted gross license income was $1.26 billion in FY 2000, up 46 percent over FY 1999.

[79] Tenth annual licensing survey released by the Association of University Technology Managers (AUTM). See <www.autm.net>

The geographical and sectoral concentrations just summarized create additional challenges to champions of early stage technology development projects located outside of favored geographical or market spaces. Such challenges may be of considerable importance to public policy. The implications for public policy will depend heavily on whether the Federal government attempts to compensate for such tendencies toward concentration, or rather to accept them as reflecting the flow of resources to geographical and market areas in which expected economic returns are highest.

Implications for Policy Design and Implementation: Lessons From the Experience of the Advanced Technology Program[80]

In 1990 Congress created the Advanced Technology Program (ATP) within the National Institute of Standards and Technology of the U.S. Department of Commerce. The program's mission is to "assist United States businesses in creating and applying generic technology and research results necessary to: (1) commercialize significant new scientific discoveries and technologies rapidly; and (2) refine manufacturing technologies … giving preference to technologies that have great economic potential."[81] Industry proposes research projects to ATP; projects are selected for funding based on both their technical and their economic and business merit.

ATP is designed to function as a form of public-private partnership, in which a government agency, NIST, promotes economic growth by sharing with industry the cost of early stage research in new or existing firms (Hill 1998: 143–173). ATP research is intended to develop innovative technologies that, despite being high in technical risk, are "enabling" in the sense of having the potential to provide significant, broad-based benefits.

The ATP program was accessible from the beginning to both individual firms and consortia of firms eager to share a new technology if it could be made practical. In 1993 the Clinton administration introduced an innovation: ATP would invite industries to propose "focus areas" for ATP investment. The idea was to produce more measurable economic effects and encourage technology diffusion by concentrating $30 to $40 million in each of several industrial technology areas. The grants themselves could be to individual firms or to groups of firms, but all would be aware of the common target area for research. This approach seemed attractive to most observers, but was terminated by the 105th Congress.

The role of universities in ATP is defined in the statute. Universities can participate in the consortia of firms proposing projects to ATP, but they cannot serve as the project leader (prime contractor). Thus, a significant fraction of ATP funding flows to university laboratories acting as subcontractors of the firms and in many cases the experts in the

[80] Description in this section of the origins and objectives of the Advanced Technology Program is drawn from chapter 5 of Branscomb and Auerswald (2001).

[81] The ATP statute originated in the Omnibus Trade and Competitiveness Act of 1988 (Public Law 100-418, 15 U.S.C. 278n), but was amended by the American Technology Preeminence Act of 1991 (Public Law 102-245). The full text of the ATP statute is available at <http://www.atp.nist.gov/eao/ir-6099/statute.htm>.

universities have also served as advisors to the firms creating the proposal, thus strongly influencing the technical goals and strategies. Universities have often sought the opportunity to act as the initiators of ATP group projects, however this would require a change in the legislation.

A recent report from the Secretary of Commerce defends the ATP program as a useful policy tool for encouraging innovation and recommends a series of six reforms in the program.[82] Two of these would give universities patent rights in projects carried out in partnership with firms and would allow universities to initiate and lead joint projects with firms. Another emphasizes that ATP should be viewed—and managed—as an R&D program, avoiding "down stream" investments in product development. Large firms would be allowed to participate only in consortia, and ATP would improve its access to expert advice. The most controversial "reform" would be a change in the law allowing ATP to recapture a 5% royalty on commercially successful projects. This is unlikely to be accepted by the Congress, and in any case seems to be philosophically incompatible with the notion that ATP does not fund product development, making the association of earnings within ATP projects difficult to establish. It also would appear to provide an incentive for ATP managers that is perverse with respect to the desire to keep the program focused on high-risk, early stage research.

Thus the direction of policy is likely to continue to be rooted in research funding policy, but to allow government agencies to invest further downstream than is traditional for government basic research funding. The application of peer review processes to this kind of work would appear to offer a serious challenge, perhaps explaining why the Defense Research Projects Agency (DARPA), which does not use peer review, is more comfortable with funding advanced technologies of industrial value than is the National Science Foundation.

Conclusion

The challenges faced today by those involved in crafting and implementing science and technology policy at the Federal level parallel those faced by the leading technology corporations in the United States in the 1960s, 70s, and 80s. These large companies generated many basic science breakthroughs in noted research facilities such as Bell Labs and the Xerox Palo Alto Research Center (PARC). Yet, in many well documented and widely discussed cases, these companies missed significant opportunities to turn inventions into profitable innovations. What is worse—in many cases the companies lost not only the inventions, but the inventors, as a result of inadequate support for the invention to innovation transition. The founder of Intel, Gordon Moore (noted also as the originator of "Moore's Law") observed last year at a conference at Stanford University: "In a pattern that clearly carries over to other technological ventures, we found at Fairchild that any company active on the forefront of semiconductor technology uncovers far more opportunities than it is in a position to pursue. And when people are enthusiastic

[82] The ATP study by the Secretary of Commerce can be found at <http://www.atp.nist.gov/atp/secy_rept/contents.htm>

about a particular opportunity but are not allowed to pursue it, they become potential entrepreneurs. As we have seen over the past few years, when these potential entrepreneurs are backed by a plentiful source of venture capital there is a burst of new enterprise."[83]

How much innovation is the right amount in a large corporation? A region? A nation? In every case, some "spillovers" or "leakage" occur of ideas, people, projects. Moore continues: "One of the reasons Intel has been so successful is that we have tried to eliminate unnecessary R&D, thus maximizing our R&D yield and minimizing costly spin-offs. But successful start-ups almost always begin with an idea that has ripened in the research organization of a large company (or university). Any region without larger companies at the technology frontier or research organizations of large companies will probably have fewer companies starting or spinning off."

A similar tension faces regions and nations as they struggle to encourage the "horizontal" connections between researchers to spur invention, at the same time that they encourage "vertical" connections between technologists and business executives in achieving the invention to innovation transition. In his Industrial Research Institute Medalist's Address provocatively titled "The Customer for R&D is Always Wrong!", Robert Frosch (former head of research at General Motors and Administrator of NASA, among other distinctions), offered the following observation:

> There is a kind of Heisenberg uncertainty principle about the coordination connections that are necessary in R&D. One needs all of these deep connections among kinds of knowledge, and the ability to think about the future, that works best in an institution that puts all those people together. One also needs connection with the day-to-day, market thinking, and the future thinking of the operating side of the business, which suggests to many that the R&D people should be sitting on the operating side of the business.
>
> This is an insoluble problem; there is no organizational system that will capture perfectly both sets of coordination… There is no perfect organization that will solve this problem—the struggle is inevitable.

Neither the United States, nor its venture capital firms, nor its large corporations, have arrived at the perfect organizational structure to manage innovation. To our knowledge, no such perfect organization exists elsewhere. If Frosch is correct (and we think he is), even in theory, fundamental contradictions inherent in the "planning of innovation" suggest that it is misguided to aspire toward elegance, symmetry, and efficiency in this context. In the Darwinian Sea, the struggle is inevitable—not just the struggle between aspiring technologies and their champions, but also the struggle between institutional forms and approaches to the management of innovation.

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[83] Moore and Davis (2000), paper prepared for the Stanford CREEG Conference "Silicon Valley and Its Imitators" July 28,2000.

The chaotic character of the "Darwinian Sea" is probably necessary to provide a wide range of alternative ways to address issues of technical risk, to identify markets that do not yet exist, to match up people and money from disparate sources. But on one bank of the Sea—the S&T enterprise, technology "push" policies may encourage agencies to fund research closer to the reduction to practice required for a solid business case. And on the other bank – the world of business and finance—technology "pull" policies will continue to enhance the incentives for risk taking (for example through moderated capital gains tax rates). Programs like the Advanced Technology Program, which has elements of both push and pull, may continue to be viewed as experimental, but will become more securely anchored on the research shore of the Sea if they are to maintain effectiveness at the same time that they secure lasting public and political support.

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Chapter 4: Federal Policy and the Development of Semiconductors, Computer Hardware and Software, and the Internet[84]

David C. Mowery

Introduction

Advances in electronics technology have created three new industries — electronic computers, computer software, and semiconductor components — in the postwar U.S. economy. These three industries combined to give birth to the Internet, a "general purpose technology" that spans these and other industrial sectors. Electronics-based innovations supported the growth of new firms in these industries, and revolutionized the operations and technologies of more mature industries, such as telecommunications, banking, and airline and railway transportation.

Federal policy played a central role in the development of all four of these technologies. The military applications of semiconductors and computers meant that defense-related R&D funding and procurement were important to the early development of these industries. The "R&D infrastructure" created in U.S. universities by defense-related and other federal R&D expenditures made significant contributions to technical developments in semiconductors, computer hardware, and computer software. The Internet itself emerged from federal programs that developed a national network linking the far-flung components of the academic and industrial R&D infrastructure that had been created with federal funds. But much more than federal R&D and procurement programs were essential to the development of these technologies and particularly, to the development of industry structures that contrasted with those of the European or Japanese electronics sectors. Federal policies in telecommunications regulation, intellectual property rights, and antitrust all influenced the development, commercialization, and widespread commercial adoption of these technologies and products based on them.

Indeed, one of the most salient conclusions from this historical overview is the need for other policies to complement R&D policy, especially if policymakers seek to support technology adoption. Although R&D programs are valuable sources of knowledge and in many cases, technological options, it is rare for R&D spending alone to promote rapid adoption of new technologies. And adoption is the critical step for the realization of the economic benefits of R&D spending.

The electronics revolution that spawned the semiconductor and computer industries, as well as the Internet, can be traced to two key innovations--the transistor and the computer. Both appeared in the late 1940s, and the exploitation of both was spurred by Cold War concerns over national security. The creation of these innovations also relied on domestic U.S. science

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[84] An earlier draft of this paper was presented at the conference on "The Government's Role in Technology Innovation: Development of Insights for Power Technologies," Washington, D.C., February 11, 2002, and benefited from comments by Lewis Branscomb and Vicki Norberg-Bohm, as well as other conference participants. Portions of this paper draw on Mowery and Rosenberg (1999) and Mowery and Simcoe (2002).

and invention to a greater extent than many of the critical innovations of the pre-1940 era. The following sections briefly survey the development of each of these four technologies, describing key aspects of their industrial and technological evolution and highlighting the role of federal policy in these developments.

Semiconductors

The transistor was invented at Bell Telephone Laboratories in late 1947, and marked one of the first tangible payoffs to an ambitious program of basic research in solid-state physics that Mervin Kelly, Bell Labs' director, had launched in the 1930s. Facing increasing demands for long-distance telephone service, AT&T sought a substitute for the repeaters and relays that would otherwise have to be employed in huge numbers, greatly increasing the complexity of network maintenance and reducing reliability. Kelly felt that basic research in the emergent field of solid-state physics might yield technologies for this purpose.[85]

Commercial exploitation of Bell Labs' discovery was influenced by the antitrust suit against AT&T filed in 1949 by the U.S. Department of Justice. Faced with this threat to its existence, AT&T was reluctant to develop an entirely new line of business in the commercial sale of transistor products, and may have wished to avoid any practice that would draw attention to its market power, such as charging high prices for transistor components or patent licenses. In April 1952, Bell Laboratories held a symposium open to all (for a $25,000 admission fee) that revealed the technology of the point contact transistor and explained progress in the manufacture of junction transistors (Brooks, 1976, p. 54). In 1956, the antitrust suit was settled through a consent decree, and AT&T restricted its commercial activities to telecommunications service and equipment. The 1956 consent decree also led AT&T, holder of a dominant patent position in semiconductor technology, to license its semiconductor patents at nominal rates to all comers, seeking cross-licenses in exchange for access to its patents. As a result, virtually every important technological development in the industry was accessible to AT&T and all of the patents in the industry were linked through cross-licenses with AT&T.

The first commercially successful transistor was produced by Texas Instruments, rather than AT&T, in 1954. Texas Instruments' silicon junction transistor was quickly adopted by the U.S. military for use in radar and missile applications. The next major advance in semiconductor electronics was the integrated circuit, which combined a number of transistors on a single silicon chip, in 1958. The integrated circuit was invented by Jack Kilby of Texas Instruments, and drew on TI's innovations in diffusion and oxide masking technologies that had initially been developed for the manufacture of silicon junction transistors. The development of the IC made possible the interconnection of large numbers of transistors on a single device, and its commercial introduction in 1961 spurred growth in industry shipments.

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[85] "As early as 1936, Kelly felt that one day the mechanical relays in telephone exchanges would have to be replaced by electronic connections because of the growing complexity of the telephone system and because much greater demands would be made on it. As this is hardly technically feasible using valves, it seems that Kelly was thinking not simply of a radically new valve technology, but perhaps of radically new electronics...It seems most likely that Kelly saw the logical progression from a semiconductor rectifier in copper oxide to be a semiconductor switch" (Braun and MacDonald, 1982, p. 36)

Kilby's search for the IC was motivated by the perceived desirability of a device that could expand the military (and, eventually, the commercial) market for semiconductor devices. Little of Kilby's pathbreaking R&D was supported by the U.S. military; the military's greatest contribution to the early development of the IC industry was its extensive purchases of these far more reliable components.

One result of the high level of federal government involvement in the early postwar semiconductor industry as both a funder of R&D and a purchaser of its products was the emergence of a structure for the innovation and technology commercialization processes that contrasted with that of pre-1940 technology-intensive U.S. industries, such as chemicals or electrical machinery, or the semiconductor industries of such nations as Germany or Japan. In a virtual reversal of the prewar situation, the R&D facilities of large firms provided many of the basic technological advances that new firms commercialized. Small-firm entrants' role in the introduction of new products, reflected in their often-dominant share of markets in new semiconductor devices, significantly outstripped that of larger firms. Moreover, the role of new firms grew in importance with the development of the integrated circuit.

Although the military market for ICs was rapidly overtaken by commercial demand, military demand spurred early industry growth and price reductions that created a large commercial market for ICs. The large volume of ICs produced for the military market allowed firms to move rapidly down learning curves, reducing component costs sufficiently to create a strong commercial IC demand.[86] Military procurement policies also influenced industry structure. In contrast to Western European defense ministries, the U.S. military was willing to award substantial procurement contracts to firms, such as Texas Instruments, that had recently entered the semiconductor industry and that had little or no history of supplying the military.[87] Interestingly, however, military R&D contracts during this period had a more modest influence on innovation. The major corporate recipients of military R&D contracts were not among the pioneers in the introduction of innovations in semiconductor technology, while the pioneering firms did so without military R&D contracts (Kleiman, 1966, pp. 173-174).

The U.S. military's willingness to purchase from untried suppliers was accompanied by conditions that mandated substantial technology transfer and exchange among U.S. semiconductor firms. To reduce the risk that a system designed around a particular IC would be delayed by production problems or by the exit of a supplier, the military required its suppliers to develop a "second source" for the product, i.e., a domestic producer that could

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[86] From the beginning, TI and other firms were aware of the commercial potential of the IC. As one of its first demonstration projects, TI constructed a computer to demonstrate the reductions in component count and size that were possible with ICs.

[87] "European governments provided only limited funds to support the development of both electronic component and computer technology in the 1950s and were reluctant to purchase new and untried technology for use in their military and other systems. European governments also concentrated their limited support on defense-oriented engineering and electronics firms. The American practice was to support military technology projects undertaken by industrial and business equipment firms that were mainly interested in commercial markets. These firms viewed their military business as a development vehicle for technology that eventually would be adapted and sold in the open marketplace." (Flamm, 1988, p. 134).

manufacture an electronically and functionally identical product. To comply with second source requirements, firms exchanged designs and shared sufficient process knowledge to ensure that the component produced by a second source was identical to the original product.

By facilitating entry and supporting high levels of technology spillovers among firms (e.g., the 1956 AT&T consent decree, the Department of Defense "second source" policy), public policy and other influences increased the diversity and number of technological alternatives explored by individuals and firms within the U.S. semiconductor industry during a period of significant uncertainty about the direction of future development of this technology. Extensive entry and rapid interfirm technology diffusion also fed intense competition among U.S. firms. The intensely competitive industry structure and conduct enforced a rigorous "selection environment," ruthlessly weeding out less effective firms and technical solutions. For a nation that was pioneering in the semiconductor industry, this combination of technological diversity and strong selection pressures proved to be highly effective.

Computers

The development of the U.S. computer industry also benefited from Cold War military spending, but in other respects the origins and early years of this industry differed from semiconductors. Although they were at best peripheral actors in the early development of semiconductor technology, U.S. universities were important sites for the early development, as well as the research, activities that produced the earliest U.S. computers. In addition, federal spending during the late 1950s and 1960s from military and nonmilitary sources provided an important basic research and educational infrastructure for the development of this new industry.

During the war years, the American military sponsored a number of projects to develop high-speed calculators to solve special military problems. The ENIAC--generally considered the first fully electronic digital computer--was funded by Army Ordnance, which was concerned with the computation of firing tables for artillery. Developed by J. Presper Eckert and John W. Mauchly at the Moore School of the University of Pennsylvania, the ENIAC did not rely on software, but was hard-wired to solve a particular set of problems. In 1944, John von Neumann began advising the Eckert-Mauchly team, which was working on the development of a new machine, the EDVAC. This collaboration developed the concept of the stored-program computer: instead of being hard-wired, the EDVAC's instructions were stored in memory, facilitating their modification.

Von Neumann's abstract discussion of the concept (von Neumann, 1945) circulated widely and served as the logical basis for virtually all subsequent computers.[88] But even after the von Neumann scheme became dominant in the 1950s, software remained closely bound to

[88] Like the semiconductor industry, but for different reasons, intellectual property rights were relatively weak in the early years of the computer industry. One reason for this was the extensive dissemination of the EDVAC report, which led Army patent lawyers to rule that "...because of the time elapsed since publication of the EDVAC report [Eckert/Mauchly/von Neumann], the concepts related to EDVAC-type machines were in the public domain. Other groups would use these ideas in designing their computers over the next few years." (Flamm, 1988, p. 50). The subsequent settlement in 1956 of a federal antitrust suit against IBM also included liberal licensing decrees, further supporting liberal interfirm diffusion of computer technology.

hardware and the organization designing the hardware generally designed the software as well. As computer technology developed and the market for its applications expanded after 1970, however, users, independent developers and computer service firms began to play prominent roles in software development.

The first fully operational stored-program computer in the U. S. was the SEAC, a machine built on a shoestring by the National Bureau of Standards in 1950 (Flamm, 1988, p. 74). A number of other important machines were developed for or initially sold to federal agencies. Among them were:

* The IAS computer, 1951, built by von Neumann at the Institute for Advanced Study on the basis of his EDVAC and subsequent papers. Funding came from the Army, the Navy, and RCA, among others.

* The Whirlwind, 1949, developed at MIT and the source of advances in computer technologies that were incorporated into the SAGE strategic air-defense system of the 1950s.

* UNIVAC, 1953, built by Remington Rand, which had bought the rights to the Eckert-Mauchly technology. Early customers included the Census Bureau and other government agencies as well as private firms.

* The IBM 701, 1953, developed by IBM and influenced by the IAS design. Originally developed as a scientific computer for the Defense Department, which bought most of the first units.

From the earliest days of their support for the development of computer technology, the U.S. armed forces were anxious that technical information on this innovation reach the widest possible audience. This attitude, which contrasted with that of the military in Great Britain or the Soviet Union, appears to have stemmed from the U.S. military's concern that a substantial industry and research infrastructure would be required for the development and exploitation of computer technology.[89] The technical plans for the military-sponsored IAS computer were widely circulated among U.S. government and academic research institutes, and spawned a number of "clones" (e.g., the ILLIAC, the MANIAC, AVIDAC, ORACLE, and JOHNIAC--see Flamm, 1988, p. 52).

As of 1954, the ranks of the largest U.S. computer manufacturers were dominated by established firms in the office equipment and consumer electronics industries. The group included RCA; Sperry Rand (originally the typewriter producer Remington Rand, which had

[89] Goldstine, one of the leaders of the wartime project sponsored by the Army's Ballistics Research Laboratory at the University of Pennsylvania that resulted in the Eckert-Mauchly computer, notes that "A meeting was held in the fall of 1945 at the Ballistic Research Laboratory to consider the computing needs of that laboratory 'in the light of its post-war research program.' The minutes indicate a very great desire at this time on the part of the leaders there to make their work widely available. 'It was accordingly proposed that as soon as the ENIAC was successfully working, its logical and operational characteristics be completely declassified and sufficient be given to the machine...that those who are interested...will be allowed to know all details.'" (1972, p. 217). Goldstine is quoting the "Minutes, Meeting on Computing Methods and Devices at Ballistic Research Laboratory," 15 October 1945 (note 14).

acquired Eckert and Mauchly's embryonic computer firm); and International Business Machines, as well as Bendix Aviation, which had acquired the computer operations of Northrop Aircraft. Sales of computers by these firms went primarily to federal government agencies, particularly the defense and intelligence agencies.

Business demand for computers gradually expanded during the early 1950s to form a substantial market. The most commercially successful machine of the decade, with sales of 1800 units, was the low-priced IBM 650 (Fisher et al. 1983, p. 17). Even in the case of the 650, however, government procurement was crucial: the projected sale of 50 machines to the federal government (a substantial portion of the total forecast sales of 250 machines) influenced IBM's decision to initiate the project (Flamm, 1988).

University research played a key role in the growth of the U.S. computer industry. Universities were important sites for applied, as well as basic, research in hardware and software, and contributed to the development of new hardware. In addition, of course, the training by universities of engineers and scientists active in the computer industry has been extremely important. By virtue of their relatively "open" research and operating environment that emphasized publication, relatively high levels of turnover among research staff, and the production of graduates who sought employment in industry, universities served as sites for the dissemination and diffusion of innovations throughout the industry. U.S. universities provided important channels for cross-fertilization and information exchange between industry and academia, but also between defense and civilian research efforts in software and in computer science generally.

Even after the emergence of a substantial private industry dedicated to the development and manufacture of computer hardware, federal R&D support aided the creation of the new academic discipline of computer science. The institution-building efforts of the National Science Foundation and the Defense Department came to overshadow private-sector contributions by the late 1950s. In 1963, about half of the $97 million spent by universities on computer equipment came from the federal government, while the universities themselves paid for 34 per cent and computer makers picked up the remaining 16 per cent (Fisher et al. 1983, p. 169).

The federal government's expanding role in supporting R&D, much of which was located in U.S. universities, during the 1950s, was supplemented by procurement spending on military systems. In both the hardware and software areas, the government's needs differed from those of the commercial sector, and the magnitude of purely technological "spillovers" from military R&D and procurement to civilian applications appear to have declined somewhat as the computer industry moved into the 1960s. Just as had been the case in semiconductors, however, military procurement demand acted as a powerful attraction for new firms to enter the industry, and many such enterprises entered the fledgling U.S. computer industry in the late 1950s and 1960s. Antitrust policy played a role here as well—another 1956 consent decree, this time settling an antitrust suit filed by the federal government against IBM, resulted in extensive licensing of this firm's patents at low royalties. Although IBM's position in computer technologies by this date was not as dominant as that of AT&T in semiconductors, the firm nevertheless had an extensive patent portfolio that became available

for license. Moreover, it is likely that IBM's willingness to pursue alleged infringers of its patents was curtailed by this federal suit and its settlement.

The Computer Software Industry[90]

By the 1980s, the rapid and interdependent development of the semiconductor and computer industries had laid the groundwork for the expansion of another "new" postwar industry, the production of standardized computer software for sale in the market (as opposed to the production of custom software for internal use). Estimates of the size and recent growth of the U.S. software market are unreliable, because of the poor quality of official statistics and the blurring of the boundaries among "hardware," "software" and "computer services." The OECD estimated that U.S. consumption of packaged software in 1999 amounted to almost $75 billion and had grown by more than 16% annually during 1990-99 (OECD, 1999), and the United States remained by far the largest packaged software market among OECD member states. According to the U.S. Commerce Department, the U.S. software industry

> has grown three times as fast as U.S. gross domestic product, created jobs at five times the rate of the private sector, and paid wages twice the national average over the last 5 years. Employment has grown at an annual rate of 10 percent over the last 10 years and 13 percent over the last 4 years. Because of its dominant position worldwide, the industry accounts for an important share of U.S. exports. BSA [the Business Software Alliance] estimates that packaged software firms had a trade surplus of $13 billion in 1997 and forecasts that the surplus will exceed $20 billion in the year 2000…(U.S. Department of Commerce, 2000, p. 28-1).

The growth of the U.S. computer software industry has been marked by at least 4 distinct eras. During the early years of the first era (1945-65), covering the development and early commercialization of the computer, software as it is currently known did not exist. The concept of computer software as a distinguishable component of a computer system was effectively born with the advent of the von Neumann architecture for stored-program computers. But the development of a U.S. software industry really began only when computers appeared in significant numbers. The large commercial market for computers that was created by the IBM 650 provided strong incentives for industry to develop standard software for this architecture.

Along with the development by IBM and other major hardware producers of standard languages such as COBOL and FORTRAN, widespread adoption of a single platform contributed to substantial growth of "internal" software production by large users. But the primary suppliers of the software and services for mainframe computers well into the 1960s were the manufacturers of these machines. In the case of IBM, which leased many of its machines, the costs of software and services were "bundled" with the lease payments. By the late 1950s, however a number of independent firms had entered the custom software industry. These firms included the Computer Usage Company and Computer Sciences Corporation, both of which were founded by former IBM employees (Campbell-Kelly,

[90] A more detailed discussion of the U.S. and other industrial nations' software industries, on which this section draws, may be found in Mowery (1998).

1995). Many more independent firms entered the mainframe software industry during the 1960s.

The second era (1965-78) witnessed the first entry of independent producers of standard software. Although independent suppliers of software began to enter in significant numbers in the early 1970s in the United States, computer manufacturers and users remained important sources of both custom and standard software during this period. Some service bureaus that had provided users with operating services and programming solutions began to unbundle their services from their software, providing yet another cohort of entrants into the independent development and sale of traded software. Sophisticated users of computer systems, especially users of mainframe computers, also developed expertise in the creation of solutions to their applications and operating system needs. A number of leading U.S. suppliers of traded software were founded by computer specialists formerly employed by major mainframe users.

Steinmueller (1996) argues that several developments contributed to the development of a large independent software industry in the United States during the 1960s. IBM's introduction of the 360 in 1965 provided a single mainframe architecture that utilized a standard operating system spanning all machines in this product family. This development increased the size of the installed base of mainframe computers that could use packaged software designed to operate specific applications, and made entry by independent developers more attractive. IBM "unbundled" its pricing and supply of software and services in 1968, a decision that was encouraged by the threat of antitrust prosecution.[91] The "unbundling" of its software by the dominant manufacturer of hardware (a firm that remains among the leading software suppliers worldwide) provided opportunities for the growth of independent software vendors. Finally, the introduction of the minicomputer in the mid-1960s by firms that typically did not provide "bundled" software and services opened up another market segment for independent software vendors.

During the third era (1978-93), the development and diffusion of the desktop computer produced explosive growth in the traded software industry. Once again, the United States was the "first mover" in this transformation, and the U.S. market quickly emerged as the largest single one for such packaged software. Rapid adoption of the desktop computer in the United States supported the early emergence of a few "dominant designs" in desktop computer architecture, creating the first mass market for packaged software. The independent software vendors (ISVs) that entered during this period were largely new to the industry. Few of the major suppliers of desktop software came from the ranks of the leading independent producers of mainframe and minicomputer software, and mainframe and minicomputer ISVs are still minor factors in desktop software.
Rapid diffusion of low-cost desktop computer hardware, combined with the rapid emergence of a few “dominant designs” for this architecture, eroded vertical integration between hardware and software producers and opened up opportunities for ISVs. Declines in the

[91] As the U.S. International Trade Commission (1995, p. 2-2) pointed out in its recent study, U.S. government procurement of computer services from independent suppliers aided the growth of a sizeable population of such firms by the late 1960s. These firms were among the first entrants into the provision of custom software for mainframe computers after IBM's unbundling of services and software.

costs of computing technology have continually expanded the array of potential applications for computers; many of these applications rely on software solutions for their realization. A growing installed base of ever-cheaper computers has been an important source of dynamism and entry into the traded software industry, because the rapid expansion of market niches in applications has outrun the ability of established computer manufacturers and major producers of packaged software to supply them.[92]

The large size of the U.S. packaged software market, as well as the fact that it was the first large market to experience rapid growth (reflecting the earlier appearance and rapid diffusion of mainframe and minicomputers, followed by the explosive growth of desktop computer use during the 1980s), gave the U.S. firms that pioneered in their domestic packaged software market a formidable "first-mover" advantage that was exploited internationally. U.S. firms' market shares in their home market exceed 80% in most classes of packaged software, and exceed 65% in non-U.S. markets for all but "applications" software.[93]

The fourth era in the development of the software industry (1992-present) has been dominated by the growth of networking among desktop computers, both within enterprises through local area networks linked to a server and among millions of users through the Internet. Networking has opened opportunities for the emergence of new software market segments (for example, the operating system software that is currently installed in desktop computers may reside on the network or the server), the emergence of new "dominant designs," and potentially, the erosion of currently dominant software firms' positions. Some network applications that are growing rapidly, such as the Worldwide Web, use software (html) that operates equally effectively on all platforms, rather than being "locked into" a single architecture. And the rapid growth of the Internet has facilitated the development of "open source" software. Although user-active innovation in software is hardly new and the exchange by users of "shareware" also has a long history, the Internet supports modifications in open-source software without the creation of competing, incompatible versions. Like the previous eras of this industry's development the growth of network users and applications has been more rapid in the United States than in other industrial economies, and U.S. firms have maintained dominant positions in these markets.

Like semiconductors and computer hardware, the U.S. computer software industry sold a large share of its output to federal government agencies, especially the Department of Defense, in its early years. There exists no reliable time series of DoD expenditures on software procurement that employs a consistent definition of software, e.g., separating embedded software from custom applications or operating systems and packaged software, etc. Nevertheless, the available, imperfect data suggest that in constant-dollar terms, DoD expenditures on software increased more than thirtyfold during the 1964-90 period (See

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[92] Bresnahan and Greenstein (1995) point out that a similar erosion of multiproduct economies of scope appears to have occurred among computer hardware manufacturers with the introduction of the microcomputer.

[93] Most analyses of packaged-software markets distinguish among "operating systems" (referred to by the U.S. Commerce Department in the most recent US Industry & Trade Outlook as "systems infrastructure software") the software used to control the operations of a given desktop, mainframe, or minicomputer, "applications," software designed to support specific, generic functions such as word-processing or spreadsheets, and "development tools," which include programming languages, application development programs, etc (See U.S. Department of Commerce, 2000, for further detail).

Mowery and Langlois, 1996). Throughout this period, DoD software demand was dominated by custom software, and DoD and federal government demand for custom software accounted for a substantial share of the total revenues in this segment of the U.S. software industry. Much of the rapid growth in custom software firms during the 1969-80 period reflected expansion in federal demand, which in turn was dominated by DoD demand. But like the semiconductor industry, defense markets gradually were outstripped by commercial markets, although the overtaking of defense by commercial demand for software appears to have taken a longer time. By the early 1990s, defense demand accounted for a declining share of the U.S. software industry's revenues.

Its declining share of total demand by the 1990s meant that the defense market no longer exerted sufficient influence on the path of R&D and product development to benefit from generic academic research and product development--defense and commercial needs had diverged. Another illustration of this tendency is the fate of the Defense Department's "generic" software language, Ada, which was unveiled in 1984. Billed as a solution to the severe problems of system maintenance and software development that had resulted from the bewildering variety of software languages in use within defense systems, Ada was intended to serve as a language that could be employed in all defense applications, and one that would attract sufficient interest from commercial developers to produce software that could be used in both civilian and military applications. But the Ada language failed to attract the attention of commercial developers, and as a result has languished.

Although demand conditions were favorable, the emergence of a vigorous independent software vendor industry in the United States rested on a research and personnel infrastructure that had benefited from an R&D infrastructure created by federal investments. Perhaps the most important result of these investments was the development of a large university-based research complex that provided a steady stream of new ideas, some new products, and a large number of entrepreneurs and engineers anxious to participate in this industry. Like postwar defense-related funding of R&D and procurement in semiconductors, federal policy toward the software industry was motivated mainly by national security concerns; nevertheless, federal financial support for a broad-based research infrastructure proved quite effective in spawning a vigorous civilian industry.

The emergent U.S. computer software industry also was a major beneficiary of postwar federal R&D spending in computer science R&D in universities and industry. Defense-related R&D spending in software appears to have declined somewhat in the 1980s, even as civilian agencies such as the National Science Foundation increased their computer science research budgets. The defense share of federal computer science R&D funding declined from almost 60% in fiscal 1986 to less than 30% in fiscal 1990 (Clement, 1987, 1989; Clement and Edgar, 1988), and defense funding of computer science R&D in universities in particular appears to have been supplanted somewhat by the growth in funding for quasi-academic research and training organizations.

U.S. antitrust policy also played an important role in this industry's development. The unbundling of software from hardware was almost certainly hastened by the threat of antitrust action against IBM in the late 1960s. Moreover, as was noted earlier, many of the

independent vendors who responded to the opportunities created by the new IBM policy had been suppliers of computer services to federal government agencies. The future of the U.S. software industry also will be influenced by the federal government's antitrust oversight of such large software firms as Microsoft. In addition, the relatively liberal U.S. policy toward imports of computer hardware and components supported rapid declines in price-performance ratios in most areas of computer hardware, and thereby accelerated domestic adoption of the hardware platforms that provided the mass markets for software producers. Western European and Japanese governments' protection of their regional hardware industries has been associated with higher hardware costs and slower rates of domestic adoption, impeding the growth of their domestic software markets.

U.S. software producers derived competitive advantages from their links with the dominant global producers of computer hardware in the early development of mainframe, minicomputer, and desktop systems. But the importance of these linkages, which was significant in the early stages of the software industry's development, appears to have declined. Nevertheless, the central position of the U.S. market as the "testbed" for developing new applications in such areas as networking and the Internet reflects the enduring importance of user-producer interactions in the software industry. Regardless of the national origin of the hardware on which new software operates, U.S.-located software firms will have advantages over firms without a presence in this market.

The Internet

The Internet is the world's largest computer network—a steadily growing collection of more than 70 million computers that communicate with one another using a shared set of standards and protocols. Together with the World Wide Web, a complementary software innovation that dramatically increased the accessibility of the network for many users, the Internet helped stimulate a communications revolution that has changed the way that individuals and institutions use computers in a wide variety of activities.

The Internet was created through a series of inventions and innovations in fields ranging from computing and communications to utility regulation, business and finance. Although its development and deployment occurred largely within the United States, the inventions embodied in the Internet originated in a more diverse set of industrial economies. Nonetheless, the United States consistently was among the first nations to improve and transform these inventions into components of a national and global network or networks, and was an early adopter of new applications.

But the history of the Internet involves more than purely technological developments. As a collection of independent but interconnected computer networks built and managed by a variety of institutions, the Internet's growth also benefited from organizational innovations. As the network evolved from its origins within a U.S. Department of Defense research project into a novel tool for educational and research organizations and subsequently, to a vast collaboration among public and private sector institutions, it drew on a number of formal and informal governance mechanisms to coordinate its standards and infrastructure.

1960-1985: Early Computer Networks

Research on computer networking began in the 1960s, roughly 15 years after the advent of the computer itself. This early research was motivated primarily by the desire to promote sharing of the scarce computing resources located at a few research centers. Like many of the early academic and industrial efforts in computing technology, much of this networking research was funded by the U.S. Department of Defense.

During the early 1960s several researchers, including Leonard Kleinrock at MIT, Paul Baran of RAND, and Donald Davies at the National Physical Laboratories in the United Kingdom, developed various aspects of the theory of packet switching.[94] Digital packet switching offered performance and reliability advantages over analog networks for data communications and was attractive to DoD-funded researchers hoping to construct a communications network that was less vulnerable to attack than the relatively centralized telephone network.[95] In order to realize these advantages, however, computer science researchers needed to develop a set of communication protocols and devices that did not rely on the circuit-switched infrastructure operated by incumbent telecommunications companies.[96] From its inception, therefore, the fundamental design advance that underpinned the Internet thus tended to weaken the market power of the dominant provider of telecommunications services in the United States.

By the late 1960s, the theoretical work and early experiments of Baran, Kleinrock and others led the U.S. Department of Defense Advanced Research Projects Agency (DARPA) to fund the construction of a prototype network. In December 1968, DARPA granted a contract to the Cambridge Massachusetts-based engineering firm of Bolt, Beranek and Newman (BBN)[97] to build the first packet switch. The switch was called an Interface Message Processor (IMP), and linked computers at several major computing facilities over what is now called a wide-area network. A computer with a dedicated connection to this network was referred to as a "host." The resulting ARPANET is widely recognized as the earliest forerunner of the Internet. (NRC, 1999a Ch. 7). By 1975, as universities and other major defense research sites were linked to the network, ARPANET had grown to more than 100 nodes.

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[94] Packet switching is fundamentally different from circuit switching, the technology that connects ordinary telephone calls. On a packet-switched network, information is broken up into a series of discrete "packets" that are sent individually, and reassembled into a complete message on the receiving end. A single circuit may carry packets from multiple connections, and the packets for a single communication may take different routes from source to destination.

[95] DARPA's support for this networking research, as well as the agency's eventual commitment to deploy a packet-switched computer network, was also motivated by the agency's interest in linking the mainframe computer systems of the academic, government, and industrial computer science research teams that it was supporting.

[96] The researchers did, however, lease the long-distance phone lines used to carry their data from AT&T.

[97] Bolt, Beranek and Newman, an MIT "spinoff" founded in 1948, was an early example of the new firms that played an important role in the Internet's development. The firm was started by MIT Professors Bruce Bolt and Leo Beranek in partnership with a graduate student, Robert Newman. Populated as it was in its early years by a mixture of recent graduates, professorial consultants, and other technical employees with close links to MIT research, BBN is a good example of the "quasi-academic" environment within which many Internet-related innovations were developed. (Wildes, 1985)

ARPANET was not the only prototype network constructed during the late 1960's and early 1970's. Donald Davies completed the construction of a data network at the National Physical Laboratories (NPL) in the UK before the development of ARPANET, and a French network called CYCLADES was built in 1972. Motivated by civilian rather than military applications, Davies proposed a national UK computer network that would have resembled ARPANET, but funding difficulties restricted the "Mark I" project to a single node located at NPL (Abbate, 2000). Cyclades introduced some significant technical advances, including datagram networking, but also had funding difficulties, and was shut down in 1978.[98]

U.S. dominance thus did not result from a first-mover advantage in the invention or even the early development of a packet-switched network. The factor that seems to distinguish ARPANET from these simultaneous projects was its sizeable public financing and flexibility in its deployment, which resulted in a prototype computer network of large scale that included a diverse array of institutions. Its size and inclusion of a diverse array of institutions as members both appear to distinguish the ARPANET from its British and French counterparts.

1985-1995: Infrastructure Development and Growth

In 1985, the NSF, by then one of several federal government agencies managing the "backbone" of the U.S. national network, made the first in a series of policy decisions that encouraged the standardization of Internet infrastructure and promoted expansion and utilization of the network. Beginning in 1985, any university receiving NSF funding for an Internet connection was required to provide access to all "qualified users" and use TCP/IP on its network. Standardization around TCP/IP encouraged interoperability and supported the creation of a large pool of university-trained computer scientists and engineers skilled in use of the protocol.

The process of infrastructure rationalization concluded with the decommissioning of the original ARPANET in 1990 and the transfer of its users and hosts to the new NSFNET. In spite of growing private-sector participation in the management of the Internet, the NSF maintained an Acceptable Use Policy (AUP) throughout this period that prohibited use of NSFNET for "commercial purposes." As more commercial users attached to the network, on their own or in partnership with academic institutions, they lobbied the NSF to abandon the AUP.

Although the NSF's Acceptable Use Policy was formally terminated in 1991, it served as an important catalyst for the creation of a private Internet backbone. Between 1987 and 1989 the major "backbone ISPs" CERFnet (California Education and Research Federation Network), PSINET, and Alternet/UUNET emerged as major providers of high-speed capacity for commercial users. (Zakon, 2000) By this time the US domestic telecommunications system was well into its lengthy transition from regulated monopoly to competitive service

[98] Datagrams are a more "pure" implementation of the packet-switching idea than the implementation used by the original ARPANET, which relied in "virtual connections" to transport messages. Pouzin's technology thus anticipated the development of TCP/IP.

provision, and the ability of these new companies to enter a growing telecommunications market was aided by the progressive restructuring and deregulation of the domestic U.S. telecommunications network. In 1995, the transition of the core network infrastructure into private hands was completed when the NSF transferred control of its four major Network Access Points to Sprint, Ameritech, MFS, and Pacific Bell.

World Wide Web

In May 1991, Tim Berners-Lee and Robert Cailliau, two physicists working at the CERN laboratory in Switzerland, released a new document format called Hyper-Text Markup Language (HTML) and an accompanying document retrieval protocol called Hyper-Text Transfer Protocol (HTTP).[99] Together, HTML and HTTP turned the Internet into a vast cross-referenced collection of multimedia documents. The collaborators named their invention the "World Wide Web" (WWW).

In order to use the World Wide Web, a computer needed a connection to the Internet and the application software that could retrieve and display HTML documents. Although it was not the first functional Internet "browser," Mosaic, a free program written by a group of graduate students at the University of Illinois' National Center for Supercomputing Applications that included Marc Andreesen, was widely adopted and accelerated the growth of the Web.[100] During 1993, the first year that Mosaic was available, HTTP traffic on the Internet grew by a factor of 3,416. By 1996, HTTP traffic was generating more packets than any other Internet application.

Although HTML and HTTP were not invented in the United States, nearly forty years of federal and private-sector investments in R&D and infrastructure supported their rapid domestic adoption and development. By the early 1990s, the basic protocols governing the operation of the Internet had been in use for nearly 20 years, and their stability and robustness had improved considerably. As Greenstein (2000a) has pointed out, the explosive growth of the Web during the 1990s benefited from the lengthy period of gestation and refinement experienced by network infrastructure.

1995-Present: Diffusion, Application and Commercialization

Although the commercialization of network infrastructure occurred gradually in response to the ponderous forces of regulatory reform and public investment, use of the Internet infrastructure to deliver commercial content and applications grew explosively during the

[99] The development of these important technical advances was motivated by Berners-Lee and Caillau's interest in facilitating the ability of physicists to archive and search the large volumes of technical papers being transmitted over the Internet as it then existed.

[100] NCSA was an NSF-funded facility devoted to research on supercomputing architecture and applications. By the early 1990s, networking technologies and powerful desktop computers had reduced the need of academic researchers for access to supercomputers. As a result, Andreesen and colleagues at the NCSA focused on developing new technologies to support expanded use of computer networking (Abbate 1999, p. 216). Federally funded "excess capacity" in the research computing infrastructure thus contributed to an important innovation in networking.

late 1990's. The magnitude of this shift is suggested by changes in the distribution of top-level domain name suffixes. In 1996, the commercial ".com" and ".net" domains contained roughly 1.8 times as many hosts as the educational .edu domain. But by 2000, the term "dot com" had become a popular expression for fledgling Internet businesses, and the .com and .net domains accounted for more than 6 times as many hosts as the .edu domain.

Federal policy and the development of the Internet

The Internet resembles many postwar innovations in information technology in that it was invented and commercialized primarily in the United States. Like the other components of the postwar "information technology industrial complex," the Internet benefited from federal policies in defense-related and civilian R&D spending, regulation, and antitrust. Federal agencies such as the Department of Defense and National Science Foundation played a critical role in funding the development and diffusion of early versions of the technology. Federal spending on R&D and procurement was complemented by the R&D investments of large corporations and the many start-ups that populated Internet-related industries. These small firms often drew on expertise developed in U.S. research universities or in large corporations and benefited from the regulatory and antitrust policies of federal agencies such as the Federal Communications Commission and the Justice Department. But the "explosive" adoption and commercial exploitation of the Internet during the 1990s built on a foundation of computer-networking R&D and investment, much of which was from federal sources, and experience in the use of this networking infrastructure, that had developed during the previous 30 years.

<u>The Role of Government-Sponsored Research</u>

Public funds were used to develop many of the early inventions that fueled the development of the Internet in the United States. Although it is tempting to attribute U.S. leadership in computer networking to a "first-mover advantage" in government-funded basic research, the development of critical technologies such as HTTP/HTML outside the United States, and the early work of non-U.S. networking pioneers such as Donald Davies and Louis Pouzin (one of the architects of the French CYCLADES network) cast some suspicion on this hypothesis. On the other hand, U.S. government agencies, such as the Department of Defense, appear to have been unique in their willingness to fund a national network infrastructure and in their support of strong links between industry and academia. Nonetheless, inasmuch as the United States government was by no means the only national government supporting domestic R&D in computer architectures and networking, the benefits of government-sponsored R&D in the United States appear to have flowed as much from scale and structure as from first-mover advantages.

Federal R&D spending, much of which was defense-related, played an important role in the creation of an entire complex of "new" postwar information technology industries (including semiconductors, computers, and computer software) in the United States. The origins of the Internet can be traced back to these efforts. Internet-related projects funded through the Department of Defense include Paul Baran's early work on packet switching, the ARPANET, and research on a variety of protocols, including TCP/IP. These public R&D

investments in networking technology were preceded by a fifteen-year DoD investment in hardware and software technology that strengthened U.S. universities' research capabilities in computer science, bankrolled the early deployment of the ARPANET, facilitated the formation of university "spinoffs" like BBN and Sun, and trained a large cohort of technical experts who aided in the development, adoption, and commercialization of the Internet.

We lack the necessary data to estimate the total federal investment in Internet-related R&D. Even were such data available, the complex origins of the Internet's various components would make construction of such an estimate very difficult. Nevertheless, federal investments in the academic computer science research and training infrastructure that contributed to the Internet's development were substantial. According to a recent report from the National Research Council's Computer Science and Telecommunications Board, federal investments in computer science research increased fivefold during the 1976-95 period, from $180 million in 1976 to $960 million in 1995 in constant (1995) dollars. Federally funded basic research in computer science, roughly 70% of which was performed in U.S. universities, grew from $65 million in 1976 to $265 million in 1995 (National Research Council, 1999a, p. 53).

In addition to their size, the structure of these substantial federal R&D investments enhanced their effectiveness. In its efforts to encourage exploration of a variety of technical approaches to research priorities, DARPA frequently funded similar projects in several different universities and private R&D laboratories. Moreover, the Department of Defense's procurement policy complemented DARPA's broad-based approach to R&D funding.[101] Contracts were often awarded to small firms such as BBN, which received the contract to build the first IMP. This policy helped foster entry by new firms into the emerging Internet industry, supporting intense competition and rapid innovation.

The large scale of the U.S. defense-related programs in computer science research and networking distinguished them from those in the United Kingdom and France; but the contrasts extend beyond the scale of these R&D programs. As was noted above, DoD program managers in information technologies, even before the establishment of DARPA, sought to establish a broad national research infrastructure in computer science that would be accessible to both civilian and defense-related firms and applications, and disseminated technical information to academic, industrial, and defense audiences. Classified R&D was important, but a great deal of U.S. defense-related R&D consisted of long-term research that was conducted in universities, which by their nature are relatively open institutions.

Another factor in the success of federal R&D programs was their "technology-neutral" character. U.S. research programs avoided the early promotion of specific product architectures, technologies, or suppliers, in contrast to efforts in other industrial economies, such as the French "Minitel" program, or celebrated postwar U.S. technology policy failures, such as the supersonic transport or the fast-breeder nuclear reactor (Nelson, 1984). The NSF, for example, focused on funding a variety of academic reesarch projects, largely through grants to university-based computer scientists.

[101] DARPA was strictly a defense R&D agency, and did not engage in large-scale procurement.

The diversity of the federal Internet R&D portfolio reflected the fact that these federal R&D investments were not coordinated by any central agency (even within the Defense Department), but were distributed among several agencies with distinct yet overlapping agendas. NASA and the DoE, for example, pursued their own networking initiatives in parallel with ARPANET during the 1970's, and DoD spending paralleled and occasionally duplicated NSF grants. In fact, the NSF's greatest single contribution to the diffusion of the Internet was the NSFNET program, which was initiated and carried out during a period of declining defense-related R&D investments in information technology. In an environment of technological uncertainty, this diversified and pluralistic program structure, however inefficient, appears to have been beneficial.

Other Federal Policies

The role of the federal government in the development and diffusion of the Internet was not limited to its financial support for R&D, but also worked through federal regulatory, antitrust, and intellectual property rights policies. The overall effect of these (largely uncoordinated) policies was to encourage rapid commercialization of Internet infrastructure, services and content by new, frequently small firms.

AT&T's failure to capture a large share of the computer networking market is a good illustration of the important role played by federal regulatory and antitrust policy. The Department of Justice's 1956 consent decree was modified in the 1982 conclusion to the federal antitrust suit against AT&T that was filed in 1974. The FCC hearings, "Computer I and II," (decided in 1971 and 1976 respectively) declared that computing lay outside the boundary of AT&T's regulated monopoly (Weinhaus, 1988). The 1956 consent decree and the FCC hearings imposed significant restrictions on AT&T's activities outside of telecommunications services. As a result, several of Bell Laboratories' major information technology innovations, including both Unix and the C programming language, were licensed on liberal terms and diffused extensively. Unix in particular was widely adopted within the academic community and played a major role in the diffusion of the computer-networking protocols (TCP/IP) that underpinned the Internet.

Federal telecommunications policy, particularly the introduction of competition in local markets following the 1984 break-up of AT&T, also affected the evolution of the Internet in the United States. The 1984 Modified Final Judgment stipulated that Regional Bell Operating Companies (RBOCs) would not be allowed into long distance until they established competitive local markets. This meant allowing Competitive Local Exchange Carriers (CLEC's) to connect to the network infrastructure on reasonable terms that would allow them to compete in various retail markets. The spread of local competition promoted the widespread availability of affordable leased lines that allowed commercial ISPs to connect their networks to long-haul carriers and one another.[102] The Telecommunications Act of 1996 reinforced competition in markets for broadband data communication.

[102] The absence of a single dominant telecommunications service provider in Finland, where several dozen firms have provided telecommunications services for much of the 20th century, also appears to have contributed to the rapid diffusion of the Internet in that nation.

State and federal regulations in the pricing of telecommunications services also aided the domestic diffusion of the Internet. State regulators have long enforced low, time-insensitive rates for local telecommunications service, in order to encourage the broadest possible access to local phone service. Regulators extended this time-insensitive pricing policy to ISPs. The FCC's May 1997 "Access Reform Order" ensured that ISPs did not have to pay the same per-minute access charges that long-distance companies pay to local telephone companies for use of the network. Unmetered local access for residential telephone services encouraged the growth of the ISP industry in local markets and the widespread diffusion of the network among residential customers, who are less sensitive to the amount of time spent online than their counterparts in countries with metered pricing for local telephone service.[103]

U.S. intellectual property rights (IPR) policy also affected the evolution of the Internet, although the influence of IPR policy is less obvious and direct than that of antitrust policy or telecommunications deregulation. Many of the key technical advances embodied in the Internet (such as TCP/IP) were placed in the public domain from their inception. This relatively weak intellectual property rights regime reflected the network's academic origins, the Defense Department's support for placing research into the public domain, and the inability of proprietary standards to compete with the open TCP/IP standard. The resulting widespread diffusion of the Internet's core technological innovations lowered barriers to the entry by networking firms in hardware, software and services.

Conclusion

This summary of a complex and lengthy history of technological and industrial development within the information technology sector highlights the important and constructive role played by federal policy. But federal policy extended well beyond the "conventional" technology policy tool of R&D spending to include telecommuniations regulation, military procurement, intellectual property rights, and antitrust policies. Although these various dimensions were not coordinated or formulated with any coherent strategy in mind, they had the effect of supporting both the "supply" of knowledge, knowhow, and trained personnel, and the "demand" for adoption of the technologies emerging from the R&D process. As a recent National Research Council report notes (National Research Council, 2001), much of DOE R&D policy has been justified in terms of supporting technology deployment, yet this policy framework provides limited support for the adoption of new energy-saving technologies.

Federal policy in information technology most clearly complemented support for R&D with support for adoption in the early years of the development of semiconductors and computers, where federal procurement contracts proved to be as influential as federal R&D awards to industrial firms in supporting innovation, entry, and the pattern of industry evolution. Federal procurement was less salient in computer software, although early federal contracts for computer support and custom software development aided the growth of at least some firms that subsequently became important suppliers of mainframe software. In the case of the Internet, the federal government underwrote the early deployment of the basic

[103] Metered pricing of local telephone service is associated with lower penetration rates for the Internet in other industrial economies.

infrastructure that provided the foundation for the explosive adoption of the browser-enabled WorldWideWeb.

This overview of federal policy in the information technology sector supports several other conclusions that may be relevant to DOE R&D policy. One defining characteristic of R&D policy and industrial development in this sector is competition. Competition among R&D funders, competition among R&D performers (including competition among R&D performers for the award of R&D and procurement contracts), competition among the various actors seeking to commercialize new applications pervaded the structure of federal programs and the dynamics of this sector. Its importance cannot be overemphasized. R&D programs (such as many in the European Union and Japan) that do not utilize competition among funders, performers, and commercializers are frequently less effective.

An important factor contributing to competition among R&D performers was the reliance on extramural R&D performers in many federal R&D programs in the information technology sector (the same could be said of federal R&D spending in biomedical science, another area of highly productive public R&D investments). U.S. research universities in particular proved to be effective sources of both basic knowledge and technological advances, as well as skilled engineers, scientists, and entrepreneurs. Much of the effectiveness of these institutions rested on the intense interinstitutional competition for resources, prestige, students, and faculty that characterizes the U.S. higher education system. Interinstitutional competition motivated university administrators and faculty to seek resources from both the federal government and industry, a competitive dynamic that proved to be highly successful in generating technical and commercial advances.

This competitive environment for R&D performers and commercializers also benefited from a tough federal antitrust policy that directly affected leading firms in the information technology sector. Leading firms in both computers and semiconductors licensed their technological portfolios more widely and at lower cost, and may have avoided pursuing infringers of their intellectual property, because of federal antitrust oversight. Antitrust policy, as well as federal R&D and procurement policies, reinforced and contributed to an environment of relatively weak intellectual property rights in these industries for much of their early years. Interfirm knowledge flows were more substantial, entry by new firms, and experimentation with new approaches to commercial applications, all were almost certainly more significant in this environment of relatively weak formal intellectual property rights that would have been true in a "strong patent" environment. The merits of strong, broad patent protection thus must be considered with care and some skepticism in the early, formative years of a new technology-based industry (See Mowery and Nelson, 1999, for further discussion).

The effectiveness of federal R&D spending in the information technology sector also was enhanced by the scale of this spending, because of the unusual character of the innovation process within such fields as software or the Internet. As Bresnahan and Greenstein (1996) have pointed out, much of the innovation process in these technologies in particular involves "co-invention" on the part of users as well as technology suppliers. The prominent role of users in developing new applications, as well as in the refinement and extension of existing

applications, is a hallmark of innovation in information technology that reaches back more than 50 years to the first business computer, developed by the Lyons Tea Shops of London to manage its "back office" transactions (See Caminer, 1998). The importance of this co-invention means that larger-scale deployment of a given new technology will spark more user-driven experimentation, thereby accelerating refinement, innovation, and improvement. The history of the Internet and the packaged software industry in the United States clearly indicate the advantages of scale. Similar advantages may well inhere in large-scale experiments with either a technological "infrastructure" or small-scale technologies in other sectors, including energy.

In short, federal R&D and other policies were of great importance to the development of the economically vibrant information technology sector, one that literally did not exist 60 years ago. But the historical structure of these federal policies differs in some important respects (notably, in intellectual property rights) from their current posture. And much of federal policy in the information technology sector seems to contrast with what one observes in the DOE energy efficiency and fossil energy programs.

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Chapter 5: Government and Technological Innovation: The Case of Agricultural Biotechnology in the United States

Calestous Juma and Muriel Calo

Introduction[104]

This report reviews progress in the commercialization of agricultural biotechnology in the United States since the industry's inception in the late 1970s, focusing on the role of the federal government. The biotechnology industry in the United States has recorded phenomenal growth and success in the past two decades and is regarded as the world leader. The commercialization of biotechnology in the United States today enjoys such success largely because by the early 1980s the government had targeted biotechnology as a technology critical for future international competitiveness. Anticipating and responding to biotechnology's needs over the course of two decades, government adapted its institutional structures and policies to support the new technology, thereby creating the enabling environment necessary for the growth and development of the industry.

Section 1 of this report provides background on the biotechnology industry. Section 2 discusses the new patent law infrastructure that was adapted during the 1980s, which provides the economic incentive the private sector needs to invest in biotechnology research and development. It also discusses international developments in intellectual property protection. Section 3 covers federal regulation of agro-biotechnology products and efforts at international harmonization. Section 4 details the federally supported research infrastructure, which relies heavily on private sector collaborations to speed the transfer of technology into the marketplace. Section 5 discusses how the government has managed relations with the public regarding the new biotechnologies. Section 6 explores the government's efforts to pave the way for the successful export of U.S. biotech products. While there have been no export promotion efforts specific to biotech, the United States has pursued international diplomacy to remove obstacles in international trade, and to pursue technology cooperation with developing nations. Section 7 concludes with a few lessons for policymakers.

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Background on the Biotechnology Industry

The biotechnology industry uses the recombinant DNA (rDNA) techniques, in which an organism's DNA is altered (for example, by adding genes from other members of the same species or from entirely different species or by removing or modifying endogenous genes) to create genetically-improved organisms. This set of techniques—the product of years of intensive basic biological research—is a tool of basic science that researchers use to contribute to the pool of knowledge about biological systems. It also opened up entirely new possibilities for applied research, spurring the founding of a new biotechnology industry. Recombinant DNA technology was exploited to develop and commercialize previously unavailable or prohibitively costly pharmaceutical products such as vaccines and human insulin. In the past twenty years, the cost of using biotechnology research tools such as rDNA, DNA sequencing, and others has declined precipitously, yielding faster financial returns for commercial biotech firms.

The biotechnology industry is one of the most research-intensive industries in the civilian manufacturing sector. In 1995, the average biotechnology company spent $68,000 per employee on research. This was more than nine times the U.S. corporate average of $7,500 that year, which reflects the fact that capital expenditures on knowledge, more than on any other input, constitute the bulk of a biotechnology firm's investment. Furthermore, the extent to which firms are able to invest in R&D is a critical factor in determining their competitiveness. For this reason, the largest of the biotechnology firms in the mid-1990s invested double and triple the amount of the average biotechnology firm, up to $209,000 per employee for Biogen, and $118,000 for Genentech (Penner, 1995). Bringing a biotechnology product to market is both a very long and very expensive process, taking up to 10 years and several hundreds of millions of dollars. Firms do not begin to see returns on their research investments, nor revenues of any kind, until several years down the line.

The new biotechnology industry was supported by the elaboration and development in the early 1980s of a national strategy of U.S. competitiveness that served to drive government policies in support of innovation, particularly in the high technologies. A number of other developed nations were busy with the same task. This work coincided with the emergence of globalization. The countries sought to enhance national competitiveness in a newly global economic arena, in the recognition that future economic growth and prosperity depended on preparing national economies to compete on the international playing field. They chose diverse approaches. Germany and France now support highly centralized government programs in biotechnology, while Japan, Sweden and the Netherlands established cohesive national strategies seeking to achieve cross-agency coordination of R&D policies and programs in biotechnology. The UK, Austria and Australia elected to designate a more diffuse grouping of applied R&D areas as priorities and sought to stimulate private sector investment through a series of fiscal measures. Switzerland, Finland, Belgium and Denmark did not establish interventionist policies directly targeting the biotechnology industry.

This report focuses on how the United States' innovation system has affected agricultural biotechnology, an area in which the United States is dominant. There has been phenomenal growth in the global cultivation of commercial transgenic crops. The estimated global area for genetically modified (GM) crops in 2001 is 130.0 million acres, representing a 19% increase, or 20.8 million acres over 2000. The growth experienced in the cultivation of GM crops between 2000 and 2001 is almost twice the corresponding increase of 10.3 million acres, or 11%, between 1999 and 2000. During the six-year period 1996 to 2001, the global area of GM crops increased more than 30-fold (with only 4.1 million acres in 1996). Just four countries are responsible for 99% of the 2001 global GM crop area: the United States, with 68% of the total, Argentina with 22%, Canada with 6%, and China with 3% (all cotton). Although China's total cultivation of GM crops is relatively modest with 3.6 million acres, the country tripled its *Bt* cotton area between 2000 and 2001, resulting in the highest year-to-year growth, while Argentina and the United States both experienced growth rates of 18%, and Canada 6%. South Africa and Australia also experienced high increases in total GM crop acreage in 2001: 33% and 37%, respectively. The other seven countries growing GM crops in 2001, reported modest increases in their total acreage, they include, listed in descending order of total acreage: Mexico, Bulgaria, Uruguay, Romania, Spain, Indonesia, and Germany (James, 2001).

The main GM crops grown globally are soybeans, with 79.9 million acres in 2001; corn, with 23.5 million acres; cotton, with 16.3 million acres, and canola, with 6.5 million acres. Indonesia reported its first commercialization of a transgenic crop, *Bt* cotton, in 2001. Brazil is poised to approve the commercialization of GM soy pending the resolution of regulatory issues. Herbicide tolerance remains the dominant trait in GM crops (in the form of *Roundup Ready Soy*) followed by insect resistance (*Bt* corn and cotton) (James, 2001).

Intellectual Property Protection

Intellectual property protection provides a key economic incentive for the development and commercialization of newly engineered agricultural products. This section discusses revisions to patent law for plant biotechnology, which have granted much greater breadth of protection than ever before, in keeping with the strategic removal of institutional barriers impeding speedy commercialization. It also discusses one of the key challenges facing government and industry as biotechnology becomes global: the effects of varying protocols and regulations on the ability of the United States to promote its products in world markets (Popper and Wagner, 2001).

Regime Development

Owners of plant varieties have enjoyed limited types of patent protections in the United States ever since the adoption of the *Plant Patent Act* (PPA) in 1930. The law conferred exclusive rights in a restricted class of asexual or vegetative reproducing plant life such as

propagated plants for agricultural uses. In 1970 the U.S. Congress enacted the *Plant Variety Protection Act* (PVPA) which extended protections for development of new varieties of sexually reproduced plants and broadened coverage to the most valuable commercial agricultural crops with a Plant Variety Protection Certificate issued through USDA. These protections were designed for plants created through conventional breeding and were inadequate for protecting products arising from biotechnology.

In 1980, the Supreme Court ruled in the landmark case of *Diamond v. Chakrabarty* that intellectual property protection could be granted for a live, human-made micro-organism. *Chakrabarty* dramatically altered intellectual property law as it relates to living matters. An important aspect of Chakrabarty was that it purported to overturn the "products of nature doctrine" and to recognize plant life as protectable subject matter under a standard utility patent. *Chakrabarty* entrenched the concept that "anything under the sun which is made by man" is patentable subject matter in the United States. The broad interpretation of patentable subject matter under *Chakrabarty* provided U.S. companies with the promise of patents to protect their investments into new technologies. As a result, U.S. industry greatly expanded its commitment to biotechnology, establishing an early position of world dominance.

In 1985, the PTO Board of Patent Appeals and Interferences (BPAI) ruled in *Ex parte Hibberd* that utility patents could be granted for "plant inventions." Plants, seeds, plant varieties, parts, processes for producing plants, plant genes, and hybrids could thereafter be claimed. *Chakrabarty* held that living organisms could be patented; the PTO ruling expressly extended this protection to plants and expanded the breadth of protection originally allowed under PPA and PVPA.[105] *Ex parte Hibbard*, essentially, held that plants, seeds, and tissue cultures can be protected by general patent law and the specific plant protection legislation. Thus, plant breeders have the right to patent a new variety of plant under both acts and under general patent law so long as they can satisfy the necessary criteria. A biotechnologist can patent a living organism upon meeting patent requirements that would apply to a mechanical invention. As a result of these and other supporting decisions, the U.S. leads the world in the scope of protection that it offers to biotechnological inventions in that "invented" living organisms can be patented and that plant varieties can both be patented and protected under plant variety statutes.

International Harmonization

As economies become increasingly global and interconnected, and the once-public domain of genetic resources becomes an increasingly valuable commodity, contradictory national patent systems and regulations governing access to genetic resources have emerged as points of international contention and dispute. The global competitiveness of agro-biotech and other high-technology industries requires a new international framework based on the resolution of these concerns.

[105] The significance of *Ex parte Hibberd* lies in the broad protection it offers which can affect more than a single variety. A utility patent can protect any plant having an inserted gene, rather than a single variety containing that gene. It also protects hybrid varieties, excluded under PVPA. Further, it does not provide for either the researcher or farmer's exception, and disallows compulsory licensing.

The Agreement on Trade-related Aspects of Intellectual Property Rights (TRIPS Agreement), signed on April 15, 1994 in Marrakech, set for the first time minimum standards of intellectual property protection. It specifies the obligation of all members of the World Trade Organization (WTO) to provide patents for both product and process inventions in all fields of technology, provided that they are new, include an inventive step, and are capable of industrial application.[106] In general, TRIPS seeks to ensure international intellectual property protection by proscribing minimum substantive standards for domestic intellectual property legislation, mandating national enforcement mechanisms, and providing international dispute settlement mechanisms.

The Convention on Biological Diversity (CBD), opened for signature in Rio de Janeiro on June 5, 1992, confirmed the basic principle of the sovereign rights of states over their natural resources, which includes the authority to determine access to genetic resources through the enactment of national legislation. The CBD addresses three distinct issues "the conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources, including by appropriate access to genetic resources and by appropriate transfer of relevant technologies taking into account all rights over those resources and to technologies."[107] Although the U.S. is not a party to the CBD, it has been an active participant in its proceedings.

Together, the TRIPS Agreement and the CBD frame complex questions of access and ownership of biological resources within the context of a very significant international debate about control and power, and ground the discussion in universally held values of conservation and sustainable use of resources. Together, they are likely to influence the future use of genetic resources to the benefit of source countries, as well as cooperating biotechnology firms.

Regulation

Both industry and the federal government recognize that a strong federal regulatory system can provide a valuable boost to public confidence in agro-biotechnology, because the level of public concern over the new technology is high. Companies have identified several private goals that the federal government believes are also in the national interest: a rigorous product review and approval process, a science-based risk assessment policy, and clear and consistent regulatory guidelines. A presidential directive in the early 1990s instructed regulatory agencies to base risk assessment of biotech products on the product itself rather than the

[106] TRIPS also stipulates that patent rights may be exercised without discrimination as to the place of invention, the field of technology, and whether products are imported or locally produced; and grants a patent term of at least twenty years. See OECD, 1996.
[107] (1992) Convention on Biological Diversity, Article 1.

process from which it was derived in keeping with the twin goals of strengthening the science-based review process and encouraging consumer confidence in GM foods. [108]

Regulatory Principles

The U.S. regulatory system for agricultural biotechnology is based on existing food safety and environmental regulations at three government agencies and uses scientific review at various stages in the development process to determine final product approval.[109] Because it is the government's policy that the human health and environmental risks posed by the new biotechnologies are essentially the same as those posed by similar products derived from conventional breeding techniques, no new legislation has been passed specifically to mandate regulation of biotechnology products largely because existing statutory authorities are considered adequate. Federal regulatory oversight focuses on the characteristics and scientifically determined risks of the biotechnology product rather than the process by which it is created. Agencies' jurisdiction over a biotechnology product is determined by the product's use.

This regulatory approach outlined above is based on the concept of "substantial equivalent". The concept has been criticized as embodying a preconceived commitment not to examine properly crops and foods improved through biotechnology. Substantial equivalence, however, is a conclusion, not a preconception, and it is reached only after crops or foods improved through biotechnology have been scrutinized against criteria laid out in OECD documents and embodied in U.S. regulations. Before a conclusion on equivalence is reached, these crops and foods must be shown not to differ from their conventional counterparts in any significant parameters relating to molecular composition, potential allergenicity or toxicity, and nutritional or dietary impact. Once questions relating to these characteristics have been asked, and answered, crops and foods improved through biotechnology can be judged to be substantially equivalent to their conventional counterparts, and thus do not require additional or special regulatory oversight. If material differences in composition or quality are revealed as a result of this scrutiny, the nature of the differences provide an indicator to regulatory authorities as to how then to proceed to ensure appropriate handling, for example, by requiring a label to indicate that a cooking oil derived from a modified canola or soybean has an improved lipid profile.

A second overarching principle of regulatory review guiding government policy is the streamlining of regulatory burden to provide biotechnology companies, as much as possible, with a predictable regulatory climate that continues to encourage and foster scientific advancement and product innovation. For those biotechnology products require review because of the risks they pose, regulatory review aims to minimize the regulatory burden while assuring the protection of public health and welfare.

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[108] "Coordinated Framework for Regulation of Biotechnology; Announcement of Policy and Notice for Public Comment," Federal Register 23, 303 (June 26, 1968).

[109] "Coordinated Framework for Regulation of Biotechnology; Announcement of Policy and Notice for Public Comment," Federal Register 23, 303 (June 26, 1968).

Roles of the Agencies

In the spring of 1984, as new biotechnology-based products began approaching the marketplace and became subject to regulations enforced by several Federal agencies because of the products' intended use, the Reagan Administration convened an interagency Biotechnology Science Coordinating Committee under the aegis of the White House Office of Science and Technology Policy (OSTP) to examine the existing regulatory framework and consider the adequacy for regulating new products of biotechnology. In June 1986, the OSTP Committee published its "Coordinated Framework for Regulation of Biotechnology" which concluded that for the most part, existing laws as currently administered by existing agencies adequately met the regulatory needs for products of the new biotechnologies. The Framework assigned leading regulatory responsibility to one federal agency for each category of product use, and established principles for coordinated reviews where agency responsibilities adjoined or overlapped.[110]

The Framework allocates regulatory responsibility to the U.S. Department of Agriculture (USDA), the Environmental Protection Agency (EPA) and the Food and Drug Administration (FDA). Under the Federal Plant Pest Act and the Federal Plant Quarantine Act, USDA — primarily through its Animal and Plant Health Inspection Service (APHIS) — regulates GM plants that have been derived from "plant pest" organisms. Plant pests include any agriculturally-harmful plant insects, mites, diseases, bateria, fungi, viruses or other parasitic plants, which are new or otherwise not widely prevalent within the United States. APHIS promulgates regulations to protect U.S. agriculture from inadvertent release or dissemination into the environment of plant-pests from GM plants.

Under the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) and the Federal Food, Drug and Cosmetic Act (FFDCA), EPA evaluates the pesticidal qualities of GM crops, such as those containing traits of pest resistance, and sets tolerance limits for substances used as pesticides on and in food and feed. EPA also establishes tolerances for residues of herbicides used on novel herbicide-resistant crops. Under FFDCA, FDA assesses the safety of all foods, food additives and animal feeds, including those produced through biotechnology.

[110] Uchtmann, 2000. In particular, the framework calls for: consistency of definitions of the organisms subject to review and consistency of regulatory scope; the clear establishment of lead and supporting agencies where regulatory oversight or review is to be performed by more than one agency, along with a mechanism for effective interagency communication; consistency of statements of information to support reviews; comparably rigorous reviews; and transparency of the review process. National Research Council, 2000a.

In July 2001, EPA issued three new rules designed to "clarify and strengthen" the agency's rules governing GM crops that produce their own pesticides. The rules address issues about so called "plant incorporated protectants" (PIPs), which are materials that enable a plant to protect itself from pests, such as insects, viruses and fungi, because the plant produces its own pesticide. PIPs derived from biotechnology are regulated by the EPA under the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) and under the Federal Food, Drug, and Cosmetic Act (FFDCA) to ensure protection of human health and the environment.

Under the rules, genetically engineered PIPs will have to meet federal safety standards as rigorous as those used for traditional pesticide registrations. If the agency determines that individual PIPs pose little or no health or environmental risk, they will be exempted from certain regulatory requirements. For example, PIPs developed through conventional breeding will be exempt from the new requirements. However, manufacturers must still report any adverse effects they identify.

The rules also exempt the DNA that creates the plant pesticide from food "tolerance" requirements—meaning there will be no federal limits on how much of the engineered DNA can remain in finished food products. This exemption does not apply to the actual pesticide produced, which will continue to be fully evaluated by the EPA to ensure that it is safe for human health and the environment.

The EPA is inviting public comments over the next 30 days on three additional exemptions, which were first proposed in 1994 but are not part of this rulemaking. The proposed exemptions are: (a) PIPs derived through genetic engineering from plants that are able to reproduce naturally; (b) PIPs that act by affecting the plant, such as causing the plant to have thicker wax cuticles; and (3) PIPs based on viral coat proteins - substances that encapsulate and protect the genetic material of certain plant viruses.

A company bringing a new GM food or crop to market will need to seek regulatory approval from as many as three separate regulatory agencies including USDA, EPA and FDA depending on the nature and intended use of the product. USDA regulations relate to field tests and growing of crops improved through biotechnology; EPA regulates applications involving plants with pesticidal properties; and FDA must be consulted for any human food or animal feed uses.

In 1992, the FDA issued a policy statement entitled "Foods Derived from New Plant Varieties" that provided guidance to developers of new plant varieties, including genetically modified varieties, on a number of regulatory issues that include when producers should voluntarily consult with the FDA on scientific issues, the design of appropriate test protocols, whether a food additive petition under Sec. 409 would be required, and the requirements for labeling (Uchtmann, 2000).

During the last days of the Clinton Administration, FDA published a proposed rule and a guideline that supplement existing regulations of foods derived from biotechnology crops. The proposed rule would require food developers of new biotechnology products to notify the agency at least 120 days in advance of their intent to market a food or animal feed developed through biotechnology and to provide appropriate information to demonstrate that the product is as safe as the conventional counterpart. FDA also announced that this information would be made public to increase the transparency of the agency's review process for such products. The current system used for GM foods on the market today calls for voluntary consultation for biotechnology products that are substantially the same as their non-biotechnology counterparts. The threat of civil liability has made the consultations tantamount to mandatory for companies; because of this, the FDA believes that all companies that have brought GM foods to market so far have participated in the consultation process. The results are available under the Freedom of Information Act. On January 18, 2001, FDA proposed to make mandatory a notification system, which would require manufactures and food companies to notify the FDA 120 days prior to releasing a genetically engineered food onto the market.

FDA also issued a draft guideline that would provide guidance for companies that want to voluntarily label their food products to designate whether the products were made with or without food ingredients developed using biotechnology. This guidance is intended to assure that claims made by food companies are truthful and not misleading, consistent with the requirements for all food products. On January 18, 2001, FDA published, for comments, in the Federal Register a *Draft Guidance for Industry: Voluntary Labeling Indicating Whether Foods Have or Have Not Been Developed Using Bioengineerin*g. In this publication, the FDA, once again, reaffirms its previously held position that most genetically engineered foods are substantially equivalent to their conventional counterparts, and as such would not require special labeling of all GM foods. In other words, the FDA believes that the use of GM, or its absence, does not itself cause a material difference in the food.

Nevertheless, in this same document, the FDA suggested that because of the strongly divergent views on labeling and the growing movement among consumer groups that advocate the labeling of all foods that were produced through the process of genetic engineering, manufacturers are encouraged to consider providing more information on the label about GM food. The information included on the label, however, must be shown to be truthful and not misleading.

Transgenic plants submitted to the regulatory review process at APHIS before they can be grown outside the laboratory are not considered to present a new category of risk when compared with conventionally bred plants (National Research Council, 2002). As a result, APHIS bases its regulatory system on the pre-existing Federal Plant Pest Act and the Federal Plant Quarantine Act. Current APHIS oversight involves three processes: notification, permitting, and petitioning for nonregulated status. APHIS uses the notification process for almost all field-testing: the applicant notifies the agency in advance of planting and receives notice of a decision within 30 days. Initially, all field testing needed to be approved by the

permitting process, but the agency determined that safety could be better assured through a streamlined notification procedure.

The Federal Role in Biotechnology Research and Enterprise Development

Since the 1940s, when the U.S. government began funding extramural research, it has substantially invested in basic research programs at universities, federal laboratories and other publicly supported institutions, while the private sector has tended to specialize in applied research where firms are able to capture a maximum of their investment in market profits. This traditional split is fading. The new research and development framework in agricultural biotechnology reflects an increasing integration of basic and applied, public and private. It is characterized overall by increased collaboration across disciplines and among institutional actors, manifesting as a rise in industry funding of relevant university research as well as more direct involvement by university scientists in technology transfer activities.[111] Large biotechnology-related firms and many smaller biotech companies are initiating or expanding in-house R&D programs while also supporting university research in areas that were previously considered relatively basic research. This section surveys the government's funding of biotech research, and its policies that provide incentives for the industry to invest in research.

Government and Private Funding for R&D

Federal funding in real dollars for agricultural research has remained stagnant since 1976 (Fuglie et al, 1996). Total private agricultural research expenditures have actually overtaken public expenditures. Total U.S. investment in agricultural research, standing at nearly $8 billion in 1998, is much larger now than it has ever been.

Although overall public research funding in agriculture remains static (contrary to recommendations made by the National Research Council in the 1980s to increase federal support to basic research [National Research Council, 1987]) biotechnology is highly targeted. A boom to the industry was the 25% Research and Experimentation tax credit (later reduced to 20%) instituted by Congress in 1981.[112] The R&E tax credit served to underwrite applied research and development costs borne by firms that are at least three years old and already have revenues. Since 1986 it has included a basic research tax credit of 20% for contractual research arrangements with universities, which was intended as a mechanism to encourage cooperative relationships between universities and industry.[113] The R&E tax credit created incentives for industry-sponsored research, including basic research, and thus serves as a source of federal funding that supplants real increases in the federal research investment.

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[111] These take the form of consulting arrangements, licensing by companies of intellectual property owned by universities, founding of and sharing of equity in start-up companies by federally-supported university inventors, etc.

[112] The *Economic Recovery Tax Act* (PL 97-34) first authorized the credit; it was subsequently renewed several times and remains on the books today.

[113] With the passage of the *Tax Reform Act* (PL 99-514).

Total private investment in agricultural research has grown very rapidly in the past two decades, coinciding with the passage of tax incentives legislation.[114] For FY 1990, USDA-funded biotechnology research expenditures were just $116 million (Office of Technology Assessment, 1991), while private agricultural research expenditures in biotechnology totaled $516 million (National Research Council, 1987 (Fuglie et al, 1996, p. 37). The NRC report recommended that by 1990, federal funding for research related to agricultural biotechnology be increased by $500 million (National Research Council, 1987, p. 81). The growth called for in the report, necessary to maintain the industry's competitiveness, may have taken place in the private sector, partially fueled by the federal tax credit.

The government supports biotechnology startups through the Small Business Innovation Research (SBIR) Program and the Advanced Technology Program (ATP), which have provided early and mid-term assistance to high technology startups since 1982 and 1988, respectively.[115] Both programs share the relatively high development risks of the new biotech firms and allow them to compete on the same level as larger, already established businesses.

The Department of Commerce's ATP Program preferentially funds projects based on university/industry partnerships,[116] while stating that research priorities are set by industry rather than government; the multi-agency SBIR Program's USDA branch states that one of its purposes is to strengthen the role of small businesses in meeting Federal research and development needs. Both programs seek to increase economic prosperity by stimulating technological innovation in the private sector: Both also require that projects be in areas of national priority.

The National Institutes of Health (NIH) contribute significant funds to the SBIR Program. Most often, NIH enters cooperative agreements with biotech companies to pursue projects in several areas of basic science: molecular genetics, DNA cloning, genetic-based diagnosis, monoclonal antibody, immunology and virology research. These collaborations facilitate the translation of basic research discoveries into commercially significant products in the health sciences. The R&D conducted under this arrangement also contributes to the broad base of knowledge underlying biotechnology that may be applied in the field of agricultural biotechnology.

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[114] The R&D tax credit is said to largely benefit established, profitable firms that house R&D programs in biotechnology, to the detriment of dedicated biotechnology companies (DBCs) which do not qualify for the credit until several years later when they begin to see earnings. Although companies can carry forward the credit fifteen years, they receive it at a sharply reduced present value.

[115] The Small Business Technology Transfer Research (STTR) Program, often mentioned hand-in-hand with SBIR, is another Federal program coordinated by the U.S. Small Business Administration which provides targeted project financing to high-technology industries as a form of non-debt risk capital.

[116] Over half of ATP's funded projects include one or more universities as either subcontractors or joint-venture members.

Other government incentive programs include preferential capital gains treatment (abolished in 1986, restored in 1997); Equipment and Facility Access Programs (EFAPs) and incubator programs providing small business low-cost access to state-of-the-art facilities; research parks; and consortia.

Biotechnology in general was a focus of Congressional decisions throughout the 1980s and 1990s. Congress has provided continuous sources of funding at NIH, USDA and other federal agencies for intramural and extramural research in the basic molecular and genomic sciences that provide the foundational knowledge to biotechnology, including applied biotechnologies. For example, in FY 1990 NIH provided an estimated $1.19 billion for basic research studies directly related to biotechnology (rDNA techniques; gene mapping and DNA sequencing; isolation, separation, and detection of DNA; protein engineering), and $1.7 billion for the broad research base underlying biotech (genetics; cellular and molecular biology; biological chemistry; immunology; virology) (Office of Technology Assessment, 1991). In a special initiative, Congress also mandated unprecedented levels of funding for the human genome project, designed to map the location of all the genes in the human body. This research has yielded major technological spin-offs in the health sciences and other fields.

Federal agricultural research funding supports both intramural and extramural research, with intramural receiving the lion's share. The USDA spends about $1.7 billion per year on research, of which $1.6 billion is distributed noncompetitively through intramural research grants to USDA staff, funds to land-grant universities, formula funds to state agricultural experiment stations, special grants for targeted initiatives, and direct grants to states. A much smaller sum, $120 million, is spent extramurally on merit-based peer-reviewed research funded by the USDA's National Research Initiative (NRI) Competitive Grants Program (National Research Council, 2000).

Congress initiated the NRI in FY 1991 with an appropriation of $73 million, rising to $120 million by 1999. NRI was created to support high-risk basic research with potential long-term payoffs, as well as interdisciplinary research emphasizing novel and innovative approaches to solving problems. Today, the NRI is widely perceived to be USDA's premier basic-research program (National Research Council, 2000, p. 42). Individual scientists and research teams, occasionally drawn from outside the traditional land-grant research establishments, compete for funding of peer-reviewed projects that characteristically run on fixed timeframes. One of the goals of the competitive grant process is to encourage recipient institutions to be more responsive to priorities established by NRI.

The NRI is comprised of six congressionally-mandated research divisions, of which the Plant Systems Division has maintained the highest and most constant funding level between 1991 and 1997, ranging from $33.2 million to $37.8 million from 1991 to 1994. It has supported as many as eleven program areas simultaneously, and now supports nine. Plant genome structure and function, molecular and cellular biology, and plant biotechnology represent three of the nine areas. The other six represent more applied fields such as plant-pest, crop plant stress, and improved nutrient qualities, which are likely to find significant advancement through biotechnologies. Unlike other divisions, the Plant Systems has experienced nearly

continuous funding of individual programs over the years (National Research Council, 2000, p. 62).

Since the 1960s, the proportion of Federal funds allocated noncompetitively as block grants have been falling: in 1970, formula funds represented 61 percent of all Federal research funds and 87 percent of USDA funds. By 1994, formula funds had fallen to 30 percent and 49 percent, respectively (Fuglie et al, 1996). Increased reliance on project-oriented support has shifted priority-setting to the USDA and other government agencies awarding funds to research institutions, allowing them to implement a more cohesive national strategy. For example, the basic biology research programs supported by NRI competitive grants are more likely than other USDA funding mechanisms to generate knowledge and technologies that can be applied nationally and transfer into industry (Fuglie et al, 1996). (Formula funds and special grants generally support research in areas such as natural resource management and rural development.)

Technology Transfer

The biotechnology industry greatly benefited from legislation passed in the 1980s that made it feasible for firms to commercialize federally funded inventions. This legislation — the *Bayh-Dole Act* of 1980, and the *Stevenson-Wydler Innovation Act* of 1980, later amended by the *Technology Transfer Act* of 1986 and then the *Technology Transfer Improvements and Advancement Act* of 1996—affected the relationships between industrial firms and federal laboratories, and between universities and industrial firms.

University-Industry collaborations have blossomed since the passage of *Bayh-Dole*. The overall increase in patents issued to universities since its passage is evidence for the increase in technology transfer in general. Until 1980, only about 4% of some 30,000 government-owned patents were licensed and the standard government policy of granting nonexclusive licenses discouraged private investment (Office of Technology Assessment, 1989). Today, the great majority of university-owned patents are licensed to industry, many in an exclusive manner.

University-industry collaborations take many forms, including industry sponsorship of university research; university ownership or interest in biotechnology firms; commercial joint ventures and research consortia between universities and industry; firms purchasing licenses in federally funded research at universities and universities and providing a share of royalties; and consulting arrangements and research contracts in return for company stock, sales percentages, positions on company boards of directors or scientific advisory boards for industry. These relationships greatly augment the speed, efficiency and overall capacity of the innovation system to transfer public research knowledge from federally supported labs to commercial enterprises. The academic entrepreneur remains near the knowledge source and is in contact with new developments in the field, which are then easily passed on to the firm.

Such relationships can also restrict information flow among researchers as a result of limits and delays on publication, and can lead to conflicts of interests when researchers have personal stakes in the outcome of their research. To resolve the conflicts inherent in private appropriation of government research, broad patents and restrictive licensing terms for patents resulting from publicly-funded collaborative R&D should be discouraged (Mowery, 1998; and Ganz-Brown, 1999, pp. 403-414).

The *Stevenson-Wydler Innovation Act* and the *Technology Transfer Act* of 1986 enabled increased R&D collaboration between industrial firms and federal laboratories through the mechanism of a Cooperative Research and Development Agreement (CRADA). Under the terms of a CRADA, the government retains intellectual property rights to the discovery but assigns a license to the participating firm. The *Technology Transfer Improvements and Advancement Act* strengthened the rights of industrial firms to exclusively license patents resulting from CRADAs, which made such arrangements more appealing to industry but limited the broad dissemination of findings that may serve the public interest. First right to exclusively license an invention, however, appears to be the powerful inducement needed for firms to agree to participate.

USDA's Agricultural Research Service (ARS) has used CRADAs to speed the transfer of technology developed in the public sector to the private sector for development of commercial applications. However, ARS has seen very few patents arise from the 900 CRADAs established through 1999. Until 1996, it was rare for collaborating firms to obtain exclusive licenses to discoveries made under a CRADA, which discouraged industry from pursuing such relationships and may explain the low incidence of patents. CRADA arrangements remain very low overall for several reasons, one of which is the frequent rejection of CRADA applications by ARS if it appears that monopolistic power over technologies with public-good value might result (Smith et al, 1999).

Integrating Education with Research

The federal government considers the integration of research and education a key feature of the national innovation system, serving several distinct purposes (See, for example, a report of the National Science and Technology Council, Office of Science and Technology Policy, 1999). These include making dual use of the federal investment in university-based research by training a new generation of scientists and engineers through the research enterprise; familiarizing that student generation with issues of importance to the federal agency engaged in the research partnership; and training and educating students so they may go on to make further contributions to the national research enterprise (Office of Science and Technology Policy, 1999). Each of these objectives can be linked within the integrated framework to federally defined areas of national priority.

For example, since it was initiated in 1998 by the Office of Science and Technology Policy, the National Plant Genome Initiative (NPGI) has targeted the sequencing of the genomes of the two model plants *Arabidopsis* and rice, and the building of a new research base in plant

genomics that includes the development of novel technologies. As the projects have moved toward functional genomics research in economically important plants, and away from building research tools, there has been a significant increase in the number of projects that integrate graduate and postdoctoral training into project activities. These projects are providing unparalleled opportunities for cross-disciplinary training in plant biology, genomics, and bioinformatics. The Plant Stress project alone has trained 26 postdoctoral researchers, 33 graduate students, and 79 undergraduates (Office of Science and Technology Policy, 2001).

Public Education

Technology Awareness

Public perceptions about biotechnology and genetic engineering are in part shaped by the public's level of awareness and general knowledge of the issues. An early Office of Technology Assessment (OTA) survey explored the degree to which the public is aware of biotechnology and genetic engineering and what the public understands them to mean, as well as perceived impacts in their lives (Office of Technology Assessment, 1987). More than a decade later, in 1999, FDA held three public hearings with the same aim as the OTA survey: to hear the views of consumers and determine the level of awareness and understanding that exists of GM foods — information which remains limited (FDA, 2000). Both activities yielded similar results. Twelve sessions were conducted in four cities.

For the most part, participants had heard about biotechnology as a new technology with great potential, primarily through media exposure, but they knew very little about how it was being applied and were vague about the details of its use. Very few had any sense of what recombinant DNA procedures involved. Overall, despite their limited technical understanding of GM food, participants had well-developed opinions about food biotechnology. Most participants recognized agro-biotech as a powerful and promising technology that offered both benefits and dangers.

For this reason, the majority of participants agreed on the need for labeling. While most participants accepted as a matter of course that the short-term safety of GM foods can be determined by science, they wanted the label to show how the food product was produced, rather than the compositional effect of the process on the food product. This demand is in striking contrast to those of other consumer research groups for nutrition labeling and use-by-date labeling, where consumers want the label to display information about product characteristics relevant to their health and safety concerns.

Finally, after discussing the prevalence of GM products in the U.S. food supply, most participants, including those who considered themselves well informed on biotechnology, registered great surprise at the pervasiveness of GM foods, and some expressed a disturbance at the lack of public information and public input to this major development.

Consumer Education

Consumer education efforts by the federal government have been sparse and irregular since the new biotechnologies became pervasive and GM food products have entered the American diet. Because the government considers these products essentially the same as conventionally-derived products, and thus they are not considered to represent new categories of risk, there have been no consistent efforts at public outreach on the subject.

Proactive engagement with the public on agro-biotech and GM foods was newly emphasized in a 2000 executive brief because of growing resistance domestically and restrictions on certain markets abroad (The White House Office of the Press Secretary, 2000). A lack of shared understanding and information was identified as one of the main causes of resistance.

The National Plant Genome Initiative has presented an unusual opportunity to conduct consumer education and outreach activities, given the scope and importance of the program and its far-reaching implications. The Missouri integrated maize mapping project of NPGI, for instance, recently received funding to construct a traveling exhibit entitled, "Superior Food Quality: Do the Tools Used to Achieve the Goal Make a Difference?" (Office of Science and Technology Policy, 2001) The goal of this project is to inform the general public on issues surrounding genetically modified organisms and to provide them with basic scientific information about crop improvement using maize as an example. The exhibit describes gene manipulation using conventional methods and genetic engineering and includes a science-based analysis of the benefits and risks for biotechnology products. The exhibit will tour field days, state fairs and other public forums over the next two years. Select NPGI investigators have also been engaged in public conversations about their work in the genomic sciences and its societal implications, appearing on PBS's Frontline, hosting undergraduate philosophy classes in the lab, giving presentations on issues related to plant biotechnology and engaging in local outreach activities.

International Trade

There is no export promotion targeted to biotech products under the various programs administered by the Foreign Agricultural Service at USDA because those products are not separated from other commodities during storage, processing and packaging, and remain unlabeled. Except within the European Union, which has instituted a ban on the import of bulk shipments of commodities (such as corn) that might contain LMOs not yet approved for planting in Europe, agricultural biotechnology products enjoy the same level of export promotion in foreign markets as do regular products. Efforts are underway to set in place an international framework governing the regulation and trade of transgenic products that will ultimately determine foreign market access for GM products. Multilateral organizations such as the World Trade Organization also offer some recourse to countries seeking to resolve international trade disputes concerning biotech products. Finally, technology cooperation efforts that involve partnerships between the United States and other countries, especially

developing countries, are also beginning to emerge as important. These collaborations enable technology transfer and will serve to drive these countries' capacity development in biotechnology.

Export Promotion

The 1996 *Federal Agriculture Improvement and Reform Act* was passed with the goal of expanding overseas markets for U.S. agricultural products by providing exporters with the tools to expand their foreign sales and to take advantage of new market opportunities.[117] The 2002 *Agricultural Risk Protection Act* replaced this legislation but preserves the key export promotion provision. Today, the United States has a sophisticated agricultural export promotion system operating on a global basis that includes technical assistance, food aid programs, and direct export promotion activities. It functions as a partnership between USDA's Foreign Agricultural Service (FAS) and numerous non-profit private sector commodity and regional associations, and is based on a principle of cost-share assistance. In FY 1998, total government expenditures for agricultural, forestry and fishery products export promotion amounted to $149.2 million; the industry share was $137.7 million (Marginnis and Carter).

USDA's Foreign Market Development Cooperator Program (FMD) and Market Access Program (MAP) are FAS's largest promotional programs. FMD is designed to expand long-term markets to promote generic or bulk agricultural commodities. The Market Access Program is intended for shorter-term, consumer-oriented promotions of high-value and processed products. FAS also provides a number of services to exporters through its overseas offices, its trade show and trade lead programs, and the Supplier Credit Guarantee Program. Other programs such as the Emerging Markets Program (EMP) provide technical assistance to improve market access for U.S. agricultural exports in emerging markets. USDA also sponsors U.S. promotions by U.S. embassies abroad, but very little information is available on those activities (Marginnis and Carter). Finally, food aid, while most often cast as a form of U.S. government assistance to the developing countries, also serves as a tool of export promotion by opening up new foreign markets to U.S. agricultural products. But recent debates over the safety of GM food donated by the United States to famine-stricken countries in Southern Africa is raising new questions regarding the overall impact of this foreign policy instrument.

Because conventional and GM agricultural products remain undifferentiated in the market, it is difficult to determine to what extent the government's promotion programs have specifically benefited biotech crops. The amount that agricultural biotech products have benefited from export promotion likely varies in proportion to their share of the exported commodity.

[117] The 1996 legislation built on the basic agricultural export programs set forth in the *Food Security Act* of 1985, which recognized trade as a major contributor to the economic health of the farm sector and was designed to shift U.S. agribulture to a more market-oriented direction. Penn, 2001.

A new FAS initiative funded by the Emerging Markets Program brings renewed support to government efforts to broaden the appeal of biotechnologies and its associated products. In FY 2001, the coordinators of the Global Biotechnology Training and Technical Assistance Program launched technical assistance and training projects in the Philippines, Chile, South Africa and Peru designed to improve understanding of the issues surrounding agricultural biotechnology. The workshops are geared to the specific concerns and constraints in each region and are targeted to key stakeholders and decision makers in what are considered important future markets for U.S. agricultural products (Beasley, 2002). Specific objectives of the workshops include informing and educating interested parties about the benefits of agro-biotech and GM crops, discussing the need for sound intellectual property rights protections, and educating regulators and scientists on the need for standardized and consistent risk assessment.

Initiatives such as this one lay the groundwork for future and long-term markets for agricultural biotechnology. They address lapses in the scientific and political knowledge base of the country and focus on conveying how the new technologies can enable solutions to long-standing challenges: economic growth, and food security. They also seek to enhance farmers', consumers' and the media's awareness and acceptance of an unfamiliar technology so that it may be grown locally and succeed in the marketplace. Programs of this nature are expected to improve U.S. trade prospects, particularly for commodities such as coarse grains, soybeans, wheat, cotton, fruits and vegetables. More significantly, they pave the way for the export of the U.S. biotech firm itself, complete with regulatory and patent law infrastructure. Of particular appeal to the industry are the new sources of genetic material.

International Diplomacy

The Cartagena Protocol on Biosafety to the Convention on Biological Diversity was adopted in January 2000 after almost five years of negotiations. It is an international environmental agreement specifically dedicated to regulating the use, handling and cross-border transfers of bio-engineered products (referred to as living modified organisms, or LMOs).[118] Because the Protocol is designed primarily to protect the environment, its key feature is a prior notification and consent regime for trade in LMOs intended for direct introduction into the environment. This regime's primary impact is on seeds exported for planting. Before genetically modified seed can gain entry to an importing country for the first time, advance government approval in the form of an Advance Informed Agreement is required (Foreign Agricultural Service, 2001b). If the seed is approved for import, shipments will need documentation specifying relevant identity traits.

[118] The Biosafety Protocol is seen by the EU and most developing countries as revisiting the WTO Sanitary and Phytosanitary (SPS) and the Technical Barriers to Trade (TBT) agreements, which were designed to limit the trade-distorting aspects of sanitary and phytosanitary measures taken by States to protect human and environmental health. Regulations dealing with food safety, food labeling, phytosanitary, animal health, and environmental aspects of biotechnology products thus come under these agreements.

Seed, however, accounts for only a small part of the overall trade in LMOs. The bulk of the LMO trade is in commodities for food, feed, and processing. The Protocol will to a large extent preserve the status quo for bulk commodities containing a biotech component by permitting shipments to remain unsegregated, but it will require notification via a Biosafety Clearing House stating that shipments "may contain" LMOs. This arrangement represents the compromise reached between the 'Miami Group' of states wanting liberalized trade (the United States, Canada, Australia, Argentina, Chile, and Uruguay), and a coalition formed by the EU, the European Community, and a bloc of over 100 "like-minded" developing countries, that wanted exporter notification of each shipment of LMO commodities. (The involvement of the U.S. was as a nonvoting state because to date, the U.S. has not ratified the CBD.) The agreement that was reached also does not require the application of the Protocol's prior notification and consent regime to shipments of LMO commodities. These steps formalize the procedure that seed and biotech companies must engage in with importing countries.

A version of the "precautionary approach" is included in parts of the Protocol that provides that a lack of scientific certainty due to insufficient knowledge or information will not prevent countries from banning imports of LMOs. There are divergent opinions on the interpretation of this approach. It is currently considered by some to be compatible with the Sanitary and Phytosanitary Agreement under the WTO (Hilllman, 2000), which considers approved products to be safe until proven otherwise (Foreign Agricultural Service, 2001a). The Protocol also upholds the right of an exporting country to challenge, under the WTO, an unwarranted decision of an importing country not to accept a biotech product. It is the view of the 'Miami Group' and others that the Protocol should preserve countries' rights under the WTO, and that any measure taken by a country must be implemented in ways that are fully consistent with that country's obligations under the WTO (Hillman, 2000).

The Protocol will enter into force following ratification by 50 countries. As of October 2002, the protocol had 36 parties. A number of key issues concerning the movement of agro-biotech products were left for future negotiation following the adoption of the Protocol: questions of liability and redress; standards for identification, handling, packaging and transport of LMOs; a definitive documentation regime for LMO commodities; compliance; and others. Finally, questions relating to the precautionary approach and the Protocol's relationship to other international agreements still need to be fully addressed.

Technology Cooperation

The United States Agency for International Development (USAID) has been involved in the area of agricultural biotechnology for more than ten years and sponsors a number of activities in agro-biotech research, policy and capacity development abroad. These efforts take the form of collaborative technology development and other transfers of technology, scientific training, institutional management of biotech R&D, intellectual property rights policies at a national and institutional level, biosafety policy development and capacity building, and public outreach (Lewis, 2002). Many of these activities are conducted through USAID's

Agricultural Biotechnology Support Project (ABSP), established in 1991 and based at Michigan University.

Ongoing research and technology development activities include:

- Collaboration between the Kenyan Agricultural Research Institute and Monsanto on the development of virus-resistant sweet potato; ABSP assisted in addressing the biosafety regulations for field testing.

- Development of molecular markers to enhance traditional breeding programs for native crops, and development of biotech crop disease diagnostics in several of the commodity-oriented Collaborative Research Support Projects, such as Sorghum/Millet and Bean/Cowpea.

- Support of the Pan African Rinderpest Campaign through the development of a heat-stable GM rinderpest vaccine for use on livestock, through a UC Davis project. The program also includes technology transfer and training of African labs to produce the vaccine and test kit locally (USAID, 2002).

Most developing nations lack the regulatory and patent law infrastructure needed to attract private sector investment in biotechnology. Capacity-building and development of the policy framework is a critical step to achieving technology transfer between the lab and the market: it allows products of research to find commercial application. It also creates a major incentive for the initial undertaking of agro-biotech research. ABSP provides much-needed assistance at the national and institutional levels to develop and implement biosafety regulations and national legal systems for intellectual property rights. Two new USAID programs will support capacity-building in these areas. The Agricultural Biotechnology Support Project II will integrate collaborative technology development with the creation of an enabling policy environment in intellectual property rights and technology transfer in order to promote biotechnology product development and use. The Program for Biosafety Systems will address biosafety training and policies to promote development, access and sustainable use of biotechnology applications in developing countries (Lewis, 2002).

Conclusion

The federal government's consistent and cohesive support for the new biotechnologies and in particular, agro-biotech, and the industry's concurrent growth and success demonstrate the importance of institutional adaptation and responsiveness as a new technology emerges. The case of agricultural biotechnology in the United States suggests three policy lessons for other high-technology sectors dependent on innovative activity.

First, competitively funded projects organized around broad "problem-driven" areas of research rather than traditional academic disciplines tend to favor the generation of innovative knowledge. The expansion of competitive grants programs such as USDA's National Research Initiative would further stimulate interdisciplinary research targeted to issues of high national priority. In general, traditional funding mechanisms have not driven the creation of innovative approaches to areas of high priority as well as competitive grants.

Second, enterprise development represents a critical stage in the development of a new technology. Small technology-intensive start-up ventures – and biotechnology firms in particular – face enormous risks during the regulatory review process and as they commercialize their new product, while already burdened with the high cost of product research and development. Fiscal policy that supports start-up ventures at this stage and enables them to compete with larger established firms (which already benefit from tax provisions such as the R&E tax credit) is critical. For example, the passage of a capital gains tax rate reduction would significantly increase investment in new biotechnology enterprises (The President's Council on Competitiveness, 1991). Small startups are carriers of innovation into the marketplace, and for this reason are integral to the success of the national innovation system. The expansion of government programs such as SBIR will also serve this goal.

Finally, the experience with commercialization of transgenic crops has revealed gaps in the knowledge base for understanding and measuring risks to the environment. A strong and credible regulatory infrastructure that inspires consumer confidence, effectively moderates risks associated with new technologies, and does not present an undue burden to industry must be founded on a consistent, scientifically based risk assessment procedure. In the case of agro-biotechnology, there is an urgent need for strategic public investment in research that fills the gaps in knowledge in our understanding of the environmental impacts of transgenic plants (National Research Council, 2002). Such research will also improve risk analysis methodologies and protocols, and would allow for improved risk assessment for conventionally bred crops as well. Regulations, in turn, need to co-evolve with technological advances. In the absence of such responsiveness, society will tend to resist and slow the technology's introduction as a result of perceived risks. In today's world of integrated economies and globalized markets, the repercussions will extend far beyond national borders. The way ahead for GM foods will depend largely on how broader societal issues related to international trade and public trust will be handled.

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Chapter 6: The Government's Role in Chemical Technology Innovation, Then and Now
Ashish Arora

Introduction

If the twenty first century is going to be the information century, then the twentieth might well have be the chemical century. The chemical industry is one the largest manufacturing industries in the world. Chemicals and allied products account for 1.5%-1.9% of the US GDP and about 10.4% of US manufacturing value added, the largest manufacturing sector in the US and second only to the food and drink sector in Europe.

Since its origins as a science based industry with the discovery of synthetic dyes in Britain in the 1850s, the chemical industry has provided a fascinating backdrop against which to study how innovation, government policy, and factor endowments interact in the process of economic growth and industrial evolution. Chemical firms provided some of the early exemplars for Chandler's magisterial historical analyses of changing firm scale and scope (1990), and for Hounshell and Smith's (1988) insightful investigation of how science and research was made to bear commercial profit at Du Pont. Studies of productivity improvements in chemical processing industries, in oil refining (Enos, 1962) and in synthetic fibres (Hollander, 1965) highlighted the importance of a sequence of small process innovations in increasing productivity.

Chemicals has been called the most "miscellaneous of industries" by David Landes, and the description is apt. The chemical processing industries stretch from the production of simple chemicals like bleach produced in the millions of tons in large scale continuous flow plants and sold at pennies a pound to complex pharmaceuticals often sold at thousands of dollars per pound. The rate and nature of technological progress naturally also differs greatly. It becomes imperative to simplify and to focus. I shall focus away from pharmaceuticals and life sciences, historically part of the chemical industry, but today surely very distinct from the chemical industry proper. Instead, I shall focus on two broad areas of innovation that might be considered general-purpose technologies for the chemical industries – polymer science and chemical process design. These two areas will provide the context for understanding the role of the government in the technological progress in the US chemical industry.

Before proceeding to the specifics, it is useful to point out that the government's role is not confined to funding research in universities and national labs or directly funding industrial research. Rather, the government influences the process of innovation in a variety of direct and indirect ways. These range from environmental regulation, which has caused firms to develop specific environmentally benign processes, to policies that affect incentives to innovate more broadly, such as protection of intellectual property and tax policy. Further, government policies that affect the education and training of engineers and scientists can also play a critical role. To say this is not to dilute science and technology policy of all useful content, but rather to provide the proper context for the main argument of this essay, which will focus on the role of government in directly funding and supporting innovation in the chemical industry.

The main argument is simple: Most significant innovations in polymers and chemical engineering are due to research, largely privately funded and typically carried out in the research laboratories of chemical and oil firms. In specific circumstances, government has played a significant role, as it did in the case of synthetic rubber research during the Second World War and afterwards.

This part is straightforward to substantiate. However, the second part of the argument is less straightforward. Although privately funded research has been the mainstay of technological innovations, changes in the structure of the industry imply that there is possibly greater need for government funding of research, particularly basic or fundamental research.

I begin with a very brief thumbnail sketch of innovation in the chemical industry, touching upon synthetic dyestuffs, polymers and chemical engineering. Industry research has been the major source of progress in these fields, along with university research (especially in the area of chemical engineering). Government has largely been in the background, although its role in synthetic rubber research is more prominent, and is discussed at some length in a later section.

The next section reviews trends in chemical R&D, which clearly show that the chemical industry has relied very little on government funding to finance its R&D. The available data also show that (Federal) government support for non-medical chemistry and chemical engineering research has been small, both as a fraction of total Federal spending on research, and as a fraction of all such spending on chemistry and chemical engineering research, and that this support has declined over time.

A Brief History of Chemical Innovation: From Synthetic Dyes to Polymers

In the 1830s and 1840s, the British had the world's dominant chemical industry, which was focused on production of inorganic chemicals.[119] The early version of the inorganic chemical industry was in some sense closer to mining than the science-based chemistry of today. Perkin's discovery of a mauve dye in 1856 launched the modern organic chemical industry. Since then, organic compounds have proved the most important class of chemicals because they are more varied and pervasive than the inorganic compounds. With synthetic dyestuffs as its engine of growth, Germany dominated the chemical industry from the 1870s until World War I. Advances in organic chemistry clarified how carbon atoms are linked to hydrogen and other atoms to form more complex molecules. Over several decades German firms developed this knowledge into a general-purpose technology for producing new dyes such as alizarin and indigo. Moreover, they soon discovered that the organic chemistry behind the creation of synthetic dyestuffs could also be harnessed for other applications such as pharmaceuticals and photographic materials.

[119] Inorganic compounds are those taken from the earth, such as salt and minerals, and which are then processed into useful products. One leading set of products were the alkalis, such as lime, soda ash, and caustic soda, used extensively in textiles, glass and fertilizers; another includes acids such as sulfuric and nitric, which are often used in tanning, textiles, dyeing, and a myriad other applications.

Academic research played a very important role in advancing the science of organic chemistry. It was vital for elucidating the chemical structure of synthetic dyes, for understanding synthetic pathways, and even for suggesting new dyes. Yet, for the most part, new dyes and methods of making them were discovered by chemists working for chemical firms, and after the 1870s, principally in Germany. It is understandable that the German lead in synthetic dyestuffs and related fields that drew upon organic chemistry is attributed to the large number of outstanding German organic chemists, and the relative neglect of organic chemistry by British government and industry. While undoubtedly correct, what made the difference, above all, was the willingness to invest in commercializing new technologies. Whereas the German chemical firms such as Bayer, BASF and Hoechst made substantial investments in research, they made much larger investments in developing new processes and in large scale manufacture, British chemical firms and investors, with only a few exceptions, failed to make the investments that mattered (Arora et al, 1999).

A great deal has been written about the role of government policies, ranging from the use of colonies as protected markets to patent protection (or lack thereof) (see e.g., Murmann and Landau, 1998; Arora et al 1999); However, it is safe to say that direct government policies, for the most part, played only a small role in explaining the rise of the German chemical industry or the decline of the British industry.

Polymer Chemistry: "Materials by Design"

If synthetic dyestuffs represented the start of "materials by design," polymer chemistry represents its maturation. The theoretical work of Herman Staudinger, Herman Mark and other German scientists in the 1920s - who postulated that many natural and synthetic materials, such as cotton, silk, and rubber consist of long chains of the same molecule linked by chemical bonds - pointed to ways of developing a series of new products by using different building-block molecules and changing the way in which these molecules were connected.

The period from 1920 to 1960 probably marks the golden age of innovation in the chemical industry, at least as far as the American chemical industry is concerned. Virtually all the major polymers – plastics and synthetic fibers – were commercialized during this period. This period also marks a number of the major developments in chemical engineering, with the commercialization of a number of important chemical processes.

As in synthetic dyes, the underlying science played a crucial role. However, private firms, whose researchers also made a number of fundamental scientific discoveries, primarily drove innovation and commercialization. Nylon is a case in point. Nylon was discovered by a research group at Du Pont, lead by Wallace Carothers. Carothers made fundamental contributions to polymer science, providing important empirical support for Staudinger's theories about the nature of polymers, and in 1931, published a famous paper where he described condensation polymerization. In addition, Carothers's group also made two discoveries of immense economic importance. In April 1930, the group discovered the first synthetic rubber which Du Pont commercialized as *neoprene*, and also discovered the technique of "cold drawing" a fiber to increase its strength. A key step in the discovery of

neoprene was Carothers's insight that the formation of very large chains (required for natural rubber) was being inhibited by the formation of water during the polymerization reaction. This lead to the development of new methods and equipment to remove water, which proved to be of great value in the next discovery, nylon, in 1934. Carothers's research also laid the groundwork for subsequent blockbusters such as polyester and acrylic, and less directly, for polyethylene and polypropylene.

As table 1 shows, virtually all the major polymers originated in corporate labs. In many cases, even fundamental scientific contributions came from researchers like Carothers, Frank Mayo (US Rubber), and Hogan and Banks (Phillips Petroleum) working for private firms. Even Paul Flory, later to receive the Nobel Prize in chemistry for his contributions to the area of polymer chemistry, worked for many years in the research department of Du Pont and other chemical firms, before moving to academia. Many other leading academic researchers and scientists such as Herman Mark and Carl Marvel also had substantial research support from industrial sources.

Table 1: Major polymer innovations: Inventors and Commercializers

Polymer	Inventor	Organization of inventor	Commercialing firm	Year of Commercialization
		Synthetic Fibers		
Nylon	**Carothers**	**Du Pont**	**Du Pont**	**1934**
Polyester	**Whinfield-Dickson**	**Calico Printers**	**ICI**	**1939**
Acrylics	**Various**		**Bayer; Du Pont**	**1920-30s (commercialized 1949-40 by Du Pont)**
		Plastics		
Phenolic resins	**Baekland; Edison and others**		**General Bakelite**	**1910**
PVC	**Fritz Klatte**	**Griesham Electron**	**Union Carbide; BF Goodrich and GE**	**1930s**
Polystyrene	**Various**		**IG Farben**	**1930**
Low Density Polyethylene	**Swallow, Perrin, Fawcett, Gibson**	**ICI**	**ICI**	**1939**
Polypropylene	**Ziegler-Natta;**	**Montecatini; Phillips Petroleum**	**Various**	**1960s**

Chemical Engineering: The Science of the Chemical Process

The success of synthetic polymers owes a great deal to a steep drop in the cost of basic petrochemicals, which are the building blocks for synthetic polymers. This cost reduction was realized through process innovation, both radical and incremental, in petrochemicals and polymers. In turn, the development of chemical engineering was key to the progress in chemical processing technologies. The job of the chemical engineer is to develop manufacturing processes for chemical products that emerged from laboratories, at unit costs that are low enough to make the product commercially viable, typically by scaling up production to produce large quantities of output in a continuous flow plant.

Chemical engineering was a distinctly American achievement, and more specifically, of the very productive university-industry interface in the United States.[120] Rosenberg's insightful account shows that American universities were chiefly responsible for developing chemical engineering as an academic discipline (Rosenberg, 1998). Even here, it is worth noting the early impetus provided by A.D. Little's early insight about all chemical processes as consisting of a combination of "unit" processes such as oxidation and reduction. Beginning with the concept of unit processes, chemical engineering was an attempt to abstract the essential and common features of chemical processes for a wide variety of products. The general-purpose nature of chemical engineering made it possible for university research and training to play an important role in applying engineering science to the practical problem of designing large-scale processes.

Even in this area, many of the basic technological breakthroughs came from corporate labs. The first significant chemical process innovation, the Haber-Bosch process was developed by BASF. A number of the major advances in catalytic refining techniques were developed by UOP, and by oil firms, notably Standard Oil. University researchers were frequently involved in these innovations, but typically in partnership with researchers from corporate labs. Lewis and Gilliland from MIT developed fluidized bed catalytic cracking in close cooperation with the chemical engineers at Standard Oil of New Jersey (Spitz, 1988, p 132).

Two Case Studies: High Octane Gasoline and Synthetic Rubber

In the case of high-octane gasoline, the government role appears to be more limited and largely one of providing a large demand. However, this large demand played a significant role in stimulating innovation in refining technology. It also stimulated advances in chemical engineering sciences, especially in the area of the design of large-scale catalytic processes.

[120]See Landau and Rosenberg (1992) for a discussion of the role of MIT in the development of chemical engineering as a discipline. The large size of the market had introduced American firms to the problems involved in large-scale production of basic products, such as chlorine, caustic soda, soda ash, and sulfuric acid as early as the beginning of this century. This focus on large-scale production had additional benefits when it turned out that the new petrochemical technologies had strong plant-level economies of scale. Because "scaling up" output was not a simple matter, and involved considerable learning, early experience with process technologies gained American firms a head start when petrochemicals became the dominant feedstock after the Second World War. In an earlier era, this head start might have been expected to last for a long time. In petrochemicals, however, the rise of a new market – for engineering and construction services, and eventually for process technology itself – allowed other countries to catch up quickly (Rosenberg, 1998).

At the start of the war, only 6000 bpd of aviation gasoline was available. In 1940, the Council of National Defense increased its estimate of the requirements from 71,300 bpd to 190,000 bpd. By 1944, 600,000 bpd were needed (Spitz, 1986, p 120). The results of the various programs for producing high-octane gasoline were impressive. By the end of 1943, 100-octane gasoline blending stock production had increased from 80,000 bpd in 1942 to 260,000 bpd, and by 1944 the industry could provide adequate fuel for defense demands. (Spitz, 1986, p 141)

Meeting these demands required not only an increase in refining capacity, but also significant innovation. Before the 1920s, gasoline was produced by distilling crude oil into its various components, which had different molecular weights, and hence, different boiling points. Since the demand for the lighter components such as gasoline, diesel and lubricants grew much faster, in the 1920s, heavier components were "cracked" using heat to increase the proportion of lighter components. However, this "thermally produced" gasoline tended to form gums in engines. In the 1930s, Eugene Houdry and others developed a catalytic process using a fixed platform with the catalyst.

The Houdry process not only produce significantly larger fraction of output in the gasoline range than thermal cracking, the gasoline had unleaded motor octane in the range of 78-80 and only required mild sulfuric acid treatment before blending into aviation gasoline. This technology had a number of limitations, principally, the process laid down coke on the catalyst bed and this had to be removed and the catalyst regenerated. In turn, this involved both technical difficulties and also limited the scale of operations. The fluidized bed catalytic cracking process (also called FCC), commercialized in 1942, addressed this problem. In addition, catalytic processes for polymerization and alkylation, also developed in the 1920s and 1930s, were of great importance for producing blending stocks, such as cumene. These were blended with the gasoline from the crackers to produce high-octane aviation fuel (Spitz, 1988, p 138).

It is clear that wartime needs and the large demand greatly hastened the development, commercialization and large-scale exploitation of these new technologies. However, the direct role of the government in coordinating these efforts was relatively modest, and many of these technologies were developed (or would have been developed) even without this impetus.[121] The government played a far more important role in the synthetic rubber program.

[121] The government, in addition to being a major buyer, also played an interesting, though not central, role in focusing research by helping define the "octane scale". The main effort was a cooperative venture between engine manufacturers and the petroleum industry. Midgley (General Motors) and Krause (Clark University) had established the relationship between the nature of hydrocarbon fuels (straight chain versus branched or aromatic) and engine knock due to premature ignition of fuel in the 1920s. Edgar (Ethyl Corporation) developed a means of rating a gasoline mixture by its "octane" number, by measuring its engine performance relative to 100% iso-octane (octane number 100). Air Force researchers determined that adding aromatics (such as cumene) to aviation gasoline improved performance for high power takeoffs, and the Petroleum Administration for War asked industry to produce suitable aromatics.

The Synthetic Rubber Research Program

This program offers an interesting instance of a government funded cooperative research program, and Morris (1989) provides a detailed account and assessment of the program. After being cutoff from regions that accounted for nearly 90% of the world's rubbers supplies, the US government formed a consortium of the leading rubber firms and some of the leading chemical firms, as well as selected university researchers, to assure rubber supplies for the country, principally through expanding the production of synthetic rubber and improving its quality. Between 1942 and 1956, the US government invested $56 million for R&D. The program was characterized by free exchange of information between the participating firms, and between them and the university groups involved in the program.[122]

The principal objectives were two fold. The first was to expand the scale of production greatly. The second challenge was to improve the quality of synthetic rubber and produce specialty rubbers, for instance, rubbers suitable for use at very low temperatures. A third objective, less explicit and of lower priority, was to develop greater knowledge and understanding of polymers.

In terms of the first objective, the program was a success. By 1945 the US produced nearly 850,000 tons of synthetic rubber, more than seven times the peak German production, achieved in 1943. This tremendous increase in the production of synthetic rubber did not require radical technological advance. Although a variety of alternative monomers (building blocks) were tried out, it turned out that butadiene and styrene, used in the Buna-S rubber patented in Germany in 1921, were the most suitable.[123] Neither was the basic process fundamentally new. However, it did require solving a variety of logistical and technological problems in expanding the supply of butadiene, for which advances in chemical engineering and petroleum refining were critical.[124]

Expanding the effective supply of synthetic rubber also required increasing the efficiency of existing processes. Though not fundamental in terms of the science involved, a number of important improvements to the polymerization process were critical in producing synthetic rubber of a higher and more consistent quality, as well as "cold rubber" a new type of synthetic rubber also made from butadiene and styrene but of higher quality in some ways, especially in being better suited for automobile tires. By 1954, two thirds of all synthetic rubber produced in the US was cold. These improvements involved better control over gel

[122] Eventually, 36 firms joined the information sharing program. The free exchange of information was mandated and in some cases, firms took special precautions to ensure that related internal projects were kept separate

[123] Buna S was called GR-S rubber in the US.

[124] Government coordination played an important role in styrene production as well. Dow Chemicals was asked by the Technical Committee to take charge and build large styrene plants in Torrance (CA), Velasco (TX) and Sarnia (ON) using Dow technology and to supervise construction of several other plants. UCC was asked to build a large plant based on its tech, and Monsanto to build an ethylbenzene-styrene plant using Dow and Monsanto technology, in partnership with Lummus. Koppers was asked to build a plant using vapor phase alkylation process using contributions by UOP, Phillips and Koppers. US production rose from less than 2m lbs per month in 1941 to 20 m lbs per month by end of 1943 and to 40 m lbs per month by end 1944. (Spitz, 1988, pp 144-46)

formation, improved modifiers, and improved emulsifiers, and in the case of cold rubber, a new catalyst as well.

Careful research also showed that the polymerization process, and hence the properties of the synthetic rubber produced, also depended upon the relative quantities of butadiene and styrene. This called for development of new analytical techniques and instruments for quality control. Once developed, they also helped provide greater understanding of the underlying reaction mechanisms and how parameters such as temperature and acidity affected the rate and outcome of polymerization. University researchers, such as Piet Koltoff, played a very important role in the development of new analytical techniques, crucial for various improvements in the process for producing synthetic rubber.

However, after World War II, a number of important innovations in synthetic rubber came either from companies not part of the government funded research program, or from research groups in participating companies but explicitly separated (in some cases, physically separated) from participating research groups. Oil extended rubber, cold rubber with added mineral oils, which was both cheaper and easier to process than cold rubber, was developed by Goodyear, and independently, by General Tire, which was not part of the research program.[125] Similarly, the new modifiers and carbon black came from Phillips Petroleum, not a member of the program until after those discoveries.

Thus neither the basic process, nor some of the important improvements in the process for synthetic rubber, can be credited to the government-funded program.[126] Indeed, Morris (1989) concludes that the government program, with its inflexible insistence on a common "recipe" to be followed by all participating companies may have delayed the adoption of a number of improvements, and was also an important reason why many of the major advances in technology came from outside the research sponsored by the program. That innovations made independently of the government program did not have to be shared and therefore, were of greater private value, doubtless also played an important role.

> The mutual recipe had been chosen to make it easier for companies to cooperate and to simply the processing stages. However, this made it more difficult to test or introduce new recipes on a large scale. It was clearly important not to disrupt the flow of sorely needed GR-S from the production plants. Such weighty reasons provided the perfect alibis for bureaucratic inertia. It is therefore not surprising that Goodrich's and Goodyear's "private" nitrile (Buna N) rubbers became the vanguard of the technology because they did not have to conform to the mutual recipe.
>
> (Morris, 1989, p 39, parentheses in the original)

[125] There were benefits, nonetheless, from Goodyear's discovery, since Goodyear, as a member of the cooperative research program, made its discovery available to all other members.

[126] Although the government research program succeeded in its immediate war time aims but not in its longer term peace time ones, the total amount of government funds at stake were small. Between 1943 and 1955 only $55 million were invested in R&D, a fraction of the nearly $700 million capital investment in synthetic rubber production 1945 alone, and less than 2% of the total value of the synthetic rubber produced over this period.

The greatest failure of the government research program, in Morris's opinion, was in the case of synthetic natural rubber (*cis*-polyisoprene).[127] Though GRS worked well for automobile tire track, natural rubber was much better for truck and airplane tires, where loads and temperatures were markedly higher. Although many of the participants, from both industry and academia, tried to develop a suitable synthetic rubber, the solution turned out to be natural rubber itself, except that it was synthesized by polymerizing isoprene, rather than from the sap of the rubber tree. The pioneering research of the German chemist, Karl Ziegler, in catalytic polymerization of polyethylene in 1950 and related materials was instrumental in this solution. However, the synthetic rubber program made at best a modest contribution to the development of *cis*-polyisoprene. Once again, the information sharing requirements imposed by the government program may have delayed the application of Ziegler's discoveries until 1955.

What is interesting is that this program succeeded best when what were required were small incremental improvements, that nonetheless, cumulatively had a large impact. Its greatest failures were in developing radical breakthroughs, and in fundamental discoveries in polymer science (although it contributed to both). This undoubtedly had much to do with the nature of the program, which started with well defined, short term aims. The priorities of the project imposed certain types of inflexibilities that hindered radical innovation. In some cases, the information sharing mandate diluted the incentives of firms to develop innovations because they would have to share the information with their rivals. Consequently, some participating firms had research groups working in rubber and polymer technologies that were carefully kept apart from the research groups participating in the synthetic rubber program. Further, the strong applied orientation of the program implied a reduced priority for the training of graduate students, resulting in a much smaller contribution to the growth of polymer science than might otherwise have been.[128]

Trends in U.S. Chemical R&D after World War II

In America, the chemical industry has been a prominent performer and funder of R&D, and it is the latter characteristic that distinguishes it from other so called "high tech" industries such as electronics, aeronautics and computers (Fig 1). Over time, the chemical industry's share of total U.S. R&D has fallen from 11 percent in 1956 to 8 percent in 1992, the last year the industry reported reasonably complete data to the NSF. (See Fig. 2) During this period the total volume of U.S. manufacturing grew threefold, but the total output of chemicals and allied products grew roughly fivefold. So while the industry was growing at a much more robust pace than the manufacturing sector as a whole, the percentage of its share of investment in R&D was decreasing.

[127] This may appear to be a contradiction in terms. However, it refers to a synthetic route to the production of natural rubber.

[128] An unforeseen benefit of the information sharing program was that it allowed a number of firms to enter the industry, particularly after the war ended and the plants were eventually sold off. This greatly increased competition and contributed to the rapid growth of the industry.

During this time, the share of Federal funds for industrial R&D in chemicals has also fallen, from a high of around 20% in 1957-58 to well below 5% in 1991 (the last year for which the NSF has systematic data for this measure). Thus, in recent years, industrial R&D in chemicals has been based almost exclusively on industry resources. Moreover, as Figure 3 shows, this is also true for industrial chemicals, implying that this is not due to the inclusion of the pharmaceuticals in SIC 28.

Federal support for chemical industry relevant research has fallen steadily no matter how one views it. Figure 4 shows that the share of chemical and chemical engineering research in federal R&D obligations has drifted downwards since 1970. As a fraction of total federal R&D obligations, this share has decreased from about 7% in 1970 to about 3% in 1998. Even if one excludes life science or medical research from the base, the share of chemical and chemical engineering research has decreased from about 10% to a little over 6% over the same time period. Finally, as Figure 5 shows, for the period 1986-1996, over 80% of the non-medical R&D associated with chemistry and chemical engineering came from company funding, with federal government funding accounting for 15-18%. Thus, whether one considers the research performed by the chemical industry or the research relevant to the chemical industry wherever conducted, government has accounted for a relatively small and declining share. Since government support for research was relatively small before World War II, the simple conclusion is that it is unlikely that government funding for technological innovation has been the driving force behind technological innovation in this industry.

Fig 1: The U.S. Chemical Industry as an R&D Performer, 1956-1992. (Source NSF)

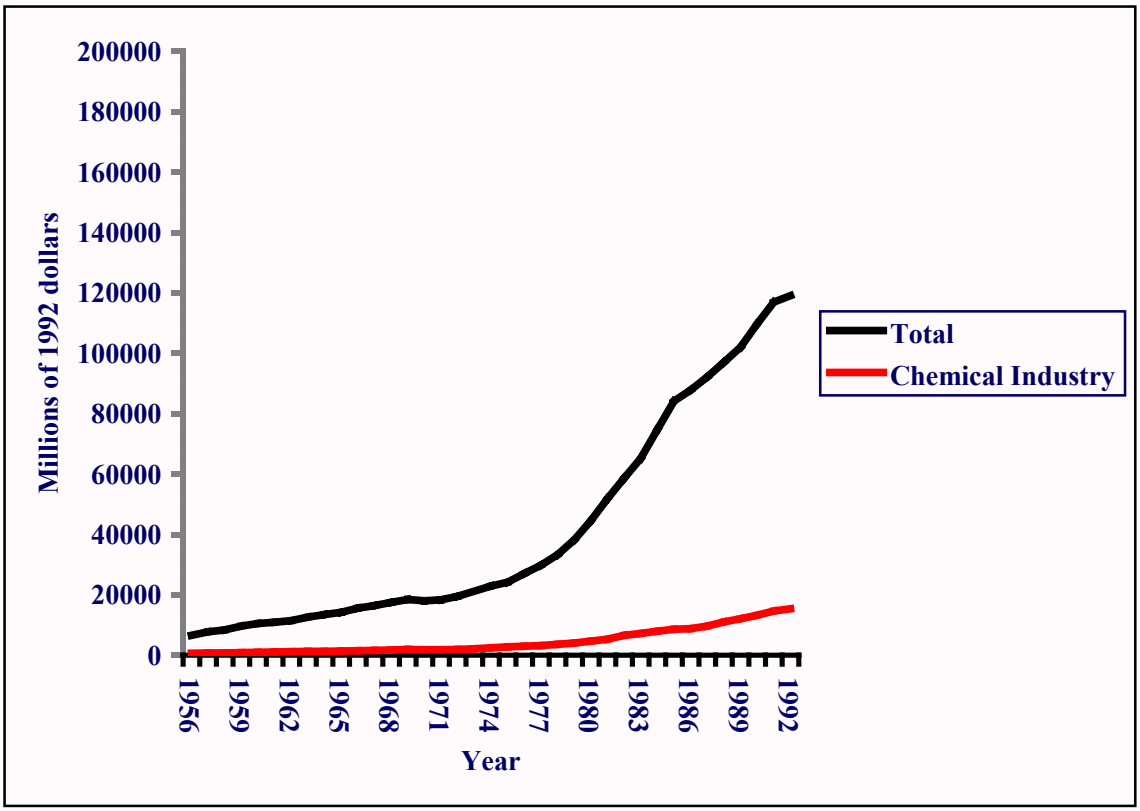


Fig 2: U.S. Chemical Industry R&D as a Percentage of Total U.S. R&D (1956-1992) source: NSF

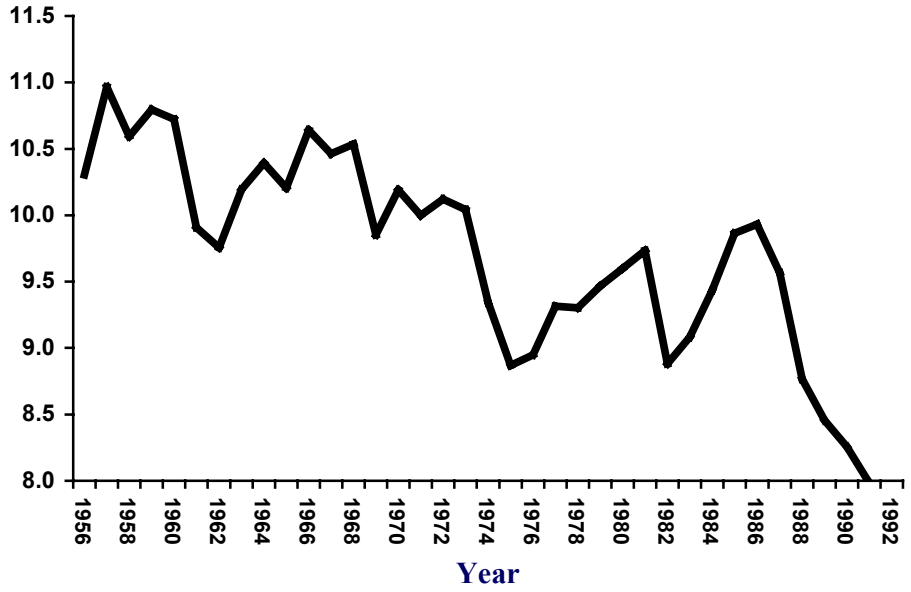


Fig 3: Share of Federal Funds in Industry R&D in Chemicals, 1957-91(Source: NSF)

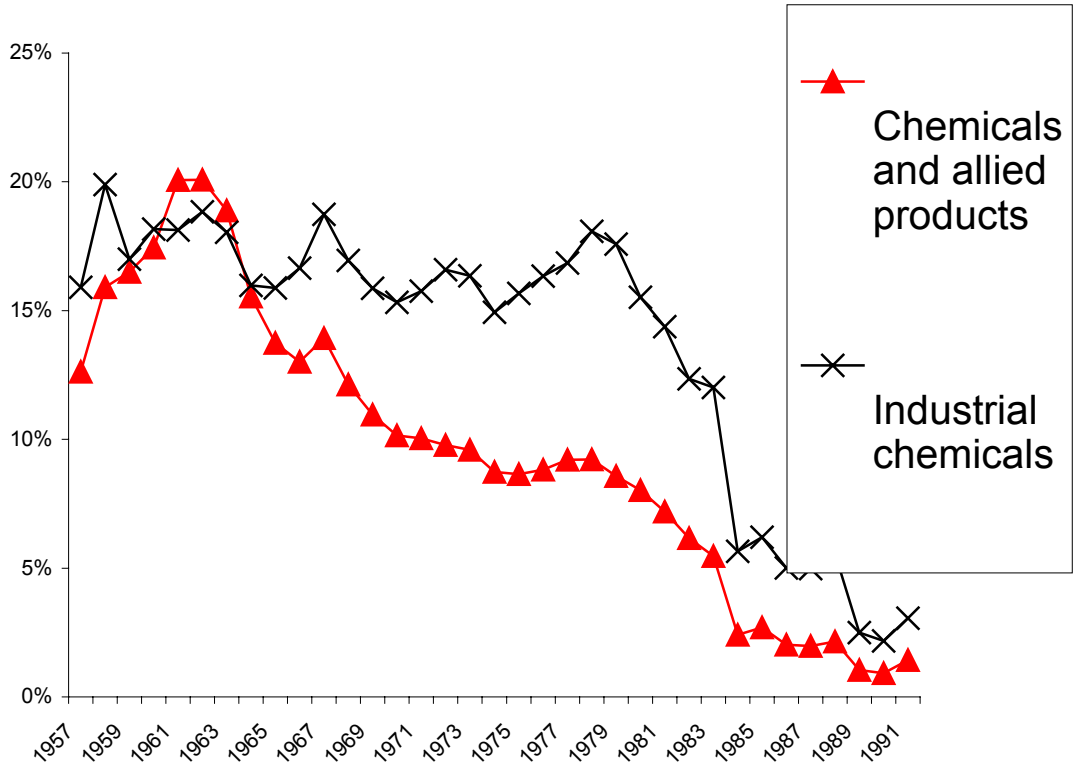
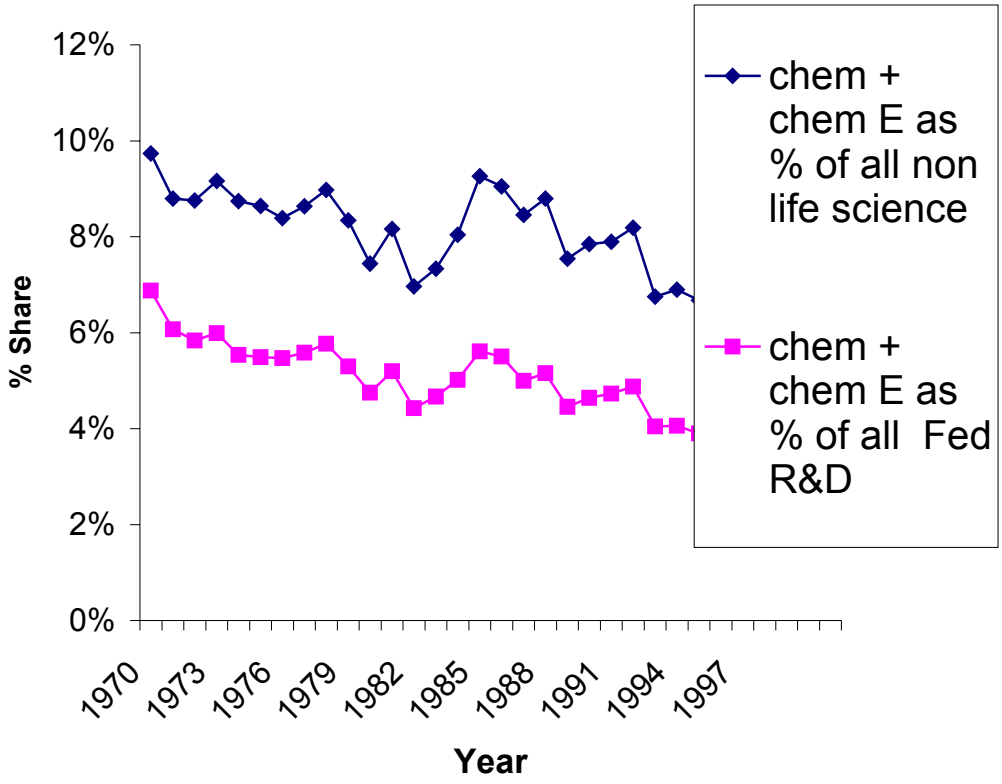


Fig 4: Share of chemical and chemical engineering research in Fed R&D obligations (source:NSF)



Role of Government

Why has the government apparently played such a limited role in technological innovation in the chemical industry, as compared, say to the semi-conductor or the electronic industry? The answer lies in part in understanding the history of the industry. Since the 1870s, chemical firms that succeeded were ones that created new products and processes. The late 19th and early 20th century were also good times for independent inventors and firms specializing in producing and selling innovations (Lamoreaux and Sokoloff, Arora and Gambardella, 1998, and Arora and Rosenberg, 1998). Thus, even though the commercialization of new technologies was long and hard, it was relatively easy to identify the value of the new knowledge being produced by chemists and chemical engineers. During the 1920s and years of the Great Depression, new products such as thermoset plastics, lacquers and semi-synthetic fibers (rayon), and new processes for petroleum refining and cracking, in turn closely related to the rapidly growing demand for automobiles, were among the few bright spots in the economy and underlined the commercial payoff from innovation.

This became ingrained in the industry. Firms did not look for new technologies from universities (although they undoubtedly looked for talent and for consultancy from university professors). Hounshell and Smith (1986) have also argued that the commercial success of nylon may have been salient in shaping the thinking of management of Du Pont, and by extension, of other chemical firms as well. Hounshell and Smith describe in detail the largely unfruitful attempts of Du Pont management to search for blockbuster products that would be as successful as nylon. In the process, Du Pont built substantial in-house capability for R&D, and for some time, even operated an in-house "Polymer Institute".

The importance of strong investments in in-house research is also exemplified by the case of Allied Chemical. In the 1920s, Allied was of comparable size and importance to Du Pont, and yet by the 1950s, it had been eclipsed by rising, research based firms such as Union Carbide, Dow Chemicals, Monsanto, Hercules and even the chemical operations of firms such as Shell and Phillips Petroleum.

However, as the chemical industry has evolved, the situation has changed quite dramatically. The United States was the dominant chemical-producing nation at the end of World War II. But the chemical industry in Europe and Japan rebuilt and grew rapidly, shifting its organic chemical production to petrochemicals nearly as quickly as the United States had.[129] The technological lead of U.S. *chemical producers* in petrochemicals was eroded as oil companies and engineering design firms diffused the technology internationally (Freeman, 1968; Arora and Gambardella, 1998). Technology for producing a variety of important products -- from the basic petrochemical inputs such as ethylene to materials such as polyethylene, polypropylene, and polyester -- became more widely available. The development of a world market in oil meant that the oil and natural gas endowments of the United States did not prove to be an overwhelming source of comparative advantage either.

By the end of the 1960s, European countries and Japan had succeeded in closing much of the gap with the United States. Since then, their relative shares in world output have largely remained constant. The major change has been the increase in chemical production outside the leading industrial countries. Indeed, today, China is the fourth largest producer in the world, behind the US, Japan and Germany. Also in the top ten producers are South Korea, Brazil and India.

The rapid growth of the chemical industry in these countries testifies to the rapid technology diffusion that took place after the big technology push in the industry during the 1950s and 60s. Maturing technology, along with increasing competition and slower demand growth, lowered the payoffs to traditional types of innovations. Faced with over-capacity, the industry restructured, beginning in the 1980s in the US, and a few years later in Western Europe. The drive to reduce cost dominated the initial restructuring phase. Major

[129] In the United Kingdom for instance in 1949 9% of total organic chemical production was based on oil and natural gas, and the proportion rose to 63% by 1962 (Chapman, 1991: 82). In Germany, the first petrochemical plant was set up in the mid-1950s, and by 1973 German companies derived 90% of their chemical feedstocks from oil. (See also Stokes, 1994.)

realignments of the product portfolios of many firms followed, with many mergers and acquisitions and the rise of entirely new firms in the industry.

During this phase, chemical firms cut down on R&D and refocused R&D expenditures on short term projects and away from more fundamental research.[130] R&D intensity in the industry has declined, if one excludes pharmaceutical related R&D. In industrial chemicals it has hovered between 4.4 and 4.1%, while in the other non-drugs sectors, it has declined steadily from 3.3% in 1986 to close to 2% in 1995.

The Role of the Government in the Future

The chemical industry is now seen as mature, a characterization accurate if one reckons chronologically. However, the maturity of the chemical industry is also meant in the sense of greatly diminished opportunity for significantly new products and processes. There is some support for the idea of maturity in the patent statistics. Narin and Albert (2001) report, based on US chemical patents filed by US based inventors, that technology cycle time for chemical patents has increased between 1980 and 1999. This roughly implies that chemical patents in 1999 are citing older patents than in 1980, and moreover, that in other areas, such as life sciences and information technology, the cycle times have decreased. Narin and Albert interpret this as implying that current chemical technology is built on relatively old prior art than in other high tech sectors, and moreover, even compared to chemical technology two decades ago.[131] In other words, chemical technology is changing less rapidly than in other high technology fields and even compared to the chemical industry of twenty years ago. Other industry observers have pointed to the absence of new radical and innovative products, as measured by whether these products have generated sales in excess of one billion dollars.

Although these trends seem to point towards a mature industry, with limited opportunity for innovation, and by implication, with little need for government support for research and development, this conclusion must be qualified. If new "billion dollar" products are far less likely, this is as much a reflection of the nature of the market and industry structure as it is of technological opportunity. There is a large installed based of capacity for producing the major plastics and synthetic fibers. Perhaps as important, there is a large installed base of experience in producing, processing, blending and using these basic polymers to deliver an incredible variety of materials. Any new polymer that hopes to capture a major share of the market has to provide dramatically superior performance on a number of fronts, an unlikely

[130] For the U.S. chemical industry as a whole, NSF figures show that the "D" of R&D accounts for about 53 percent of the total. In industrial chemicals, however, the share of development tends to be higher and appears to have risen over time. Although changes in definition and coverage make precise comparisons difficult, the available data show that for company-financed R&D, the share of development increased from about 53 percent in 1989 to 62 percent in 1995.

[131] "Technology Cycle Time is defined as the median age of the earlier U.S. patents referenced on the front page of a U.S. patent. It is a measure of the speed at which a company or industry is innovating. … Cycle time for U.S.-invented Chemicals patents seems to slow from about 8 years in TCT in 1980 to about 11 years in 1999, during which time the TCT for Life Sciences has shortened from 10 to 9.5 years. … Electronics and Information Technology are much faster with cycle times around 7 years, with Information Technology changing even faster." (Narin and Alberts, 2001)

occurrence. Furthermore, compared to the 1960s and even the 1970s, competition in the chemical industry is far more global. Companies from countries that have traditionally not been major players in this industry, such as Taiwan, Korea, China and India, have emerged on the world chemical markets. Almost always, these firms are employing technology purchased from European, American or Japanese chemical firms. Firms in the developed countries have seen market shares and profitability fall with increasing competition.

Under these conditions, it is only to be expected that patents would tend to cite older patents. Competitive pressures drive private R&D towards more specialized "solutions", reducing the potential for large volumes of production, and thereby, also reducing the ability of firms to amortize large investments in basic research (as opposed to applied research and development).

But changes in the structure of the chemical industry imply that the one cannot infer opportunities for socially valuable investments by looking at how the private sector perceives privately profitable opportunities. Indeed, one might argue that the traditional market failures associated with research and development are now more acute. Simply put, until the 1980s, the chemical firms that were leaders in R&D also had significant market shares in individual products, as well as a broad range of products sharing a common technical basis. Thus, these firms could appropriate a large enough fraction of the benefits from their research investments, particularly in more fundamental or basic research (Nelson 1959). Over time, not only has globalization and competition increased, but also the corporate portfolios have become narrower and more specialized as a part of a far reaching industrial restructuring (Arora and Gambardella, 1998). Thus, one would expect both a reduction in private R&D and a refocusing of R&D towards more applied projects. The point is that it would be incorrect to infer from this that there had been a significant diminution of opportunities for technical and scientific advance in the industry.

Indeed, patent statistics reported by Narin and Albert also show that chemical innovation draws upon fundamental knowledge of chemistry and chemical engineering: They show that chemical innovations are second only to inventions in the life sciences in drawing upon such scientific research. Indeed, ironically enough, the extent to which chemical inventions draw upon on scientific research has increased markedly in the 1990s, more so than in electronics or information technology, and again, second only to the life sciences in this regard.

The evidence suggests not so much a diminution in the *technical* opportunities as in the economic opportunities. Thus, government support has decreased precisely at a time when private incentives to invest in research have been attenuated. The decline in private investment in R&D reflects a perception that privately profitable opportunities for such investments have declined.[132] It is unclear at this time, but definitely worth further investigation, as to whether socially valuable opportunities have also declined.

[132] A recent report issued by the Council on Chemical Research provides more detail to substantiate the argument that both private and social rates of return on chemical R&D are high.

There are a number of promising areas of technical advance that build upon the notion of "material by design". Prominent among these are development of new catalysts and catalyst systems that provide greater control over the process, reduced pollutants and by products, and greater energy efficiency. In this situation, it becomes more important to ensure that the stock of basic scientific and engineering knowledge grows. Moreover, private research cannot be relied upon to shoulder the burden to the same extent. Public funding for basic research is more important than before.

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Chapter 7: Pushing and Pulling Technology into the Marketplace: The Role of Government in Technology Innovation in the Power Sector[133]

Vicki Norberg-Bohm

Introduction

In order to alleviate environmental problems and to protect national security, the future of our power system must look radically different than the system currently in place. While there is little doubt that government must take a role in making this happen, there remains considerable debate over what this role should be and how to execute it effectively. This paper addresses these questions by drawing on knowledge of the process of technological innovation and on in-depth histories of the development and deployment of three energy technologies: solar photovoltaics, wind turbines, and gas turbines.

The key conclusions of this paper are as follows. First and foremost, government has an important role to play throughout the process of innovation – from invention through diffusion. During the period spanning pre-commercialization through lead adoption, for many energy sector technologies the government will need to employ both "supply-push" and "demand-pull" strategies. Supply-push policies stimulate investment in R&D for new technologies, and in addition to government sponsorship of R&D, include policies such as R&D tax credits. Demand-pull policies create markets for emerging technologies, and include a range of approaches such as regulatory standards, subsidies and taxes, and information-based approaches such as labeling. A second conclusion is that during the period spanning pre-commercialization through lead adoption, supply-push policies are best organized as public-private partnerships.

The paper is organized as follows. The next section explores the rationales for government involvement in the various phases of technology innovation, both generally and with attention to factors specific to the energy sector that lay the basis for a more expanded role for government in energy technology development and deployment. The following section explores these ideas by examining long-term histories of the government's role in the development of three power technologies: gas turbines, wind turbines, and solar photovoltaics. It presents specific lessons on the use of supply-push and demand-pull approaches and on the use and design of public-private partnerships. This paper concludes with a discussion of the implications of these findings for future energy policy.

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[133] The research discussed in this document is part of two larger research projects: *Technology Innovation for Global Change: The Role of Assessment, R&D and Regulation* sponsored by the Integrated Assessment program, Biological and Environmental Research (BER), U.S. Department of Energy (grant DE-FG02-99ER62747); and *Government-Initiated Voluntary Programs and Public/Private Collaborations and Partnerships* sponsored by the Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy (grant #DE-FG01-00EE10759). I have gained many insights from the other researchers on these projects: William Clark, John Holdren and Robert Margolis. This paper has benefited from the comments by Bill Babiuch, Rene Kemp, Douglas Norland, and Bob Van der Zwaan. I have also benefited from comments by my colleagues in the Science, Technology and Public Policy seminar series at the Belfer Center for Science and International Affaris, Harvard University.

The Process of Technology Development and Commercialization: Rationales for an Active Role for Government in Energy Technology

At least since World War II, there has been a consensus in the United States that the government should invest in basic scientific and technological research. Although technological innovation is one of the key underpinnings for economic growth, the private sector under-invests in fundamental research. This is for two reasons. First, the outcomes of R&D are uncertain and firms are risk adverse. Second, because knowledge is a public good, individual researchers or firms often cannot retain all of the benefits from investment in R&D (i.e. knowledge spillovers). In other words, despite high private returns to investment in R&D, the public returns are even greater. Government investments in basic scientific R&D have been aimed at bringing R&D to a more optimal level, and thus realize the public interest in economic growth as well as other public missions such as security, agriculture, and health.[134]

More recently, researchers have demonstrated that funding for basic scientific and technological R&D may be inadequate to support commercialization, noting that many promising technologies are abandoned prior to successful commercialization due to shortages of finance, research, information and trust (Preston 1997, Branscomb and Auerswald 2001, Chertow 2001). Preston (1993) defines this as a "gap" that occurs "between a point where the government considers the technology too applied for additional funding and industry considers the technology too embryonic to adopt."[135] Similarly, Branscomb and Auerswald (2001) define this as a gap between research funding, which is often financed by government, and having a technology that is ready and attractive for venture capital funding. This provides a rationale for government involvement closer to commercialization, i.e. in applied R&D and demonstration and not just in basic R&D. This funding gap is particularly problematical for technologies with long lead times and a need for considerable applied research and testing between invention and commercialization, as is the case for many energy technologies.

The need for government funding for research, development, and demonstration discussed above certainly applies to cleaner energy technologies. The more controversial argument made in this paper is that in the case of cleaner energy technologies there are additional reasons for government involvement not only prior to commercialization, but also during diffusion. The first and foremost reason is market failure – the public benefits associated with energy production and consumption, including environmental externalities, security risks, and economic competitiveness, are not reflected in the market prices of energy. These externalities operate to create under-investment throughout the process of technological change. Secondly, there is often a need for complementary infrastructure and institutional development. For example, one cannot have rooftop PV without changes in metering rules, or electric cars without recharging stations. These infrastructure and institutional issues require solving collective action problems and thus may require government intervention.

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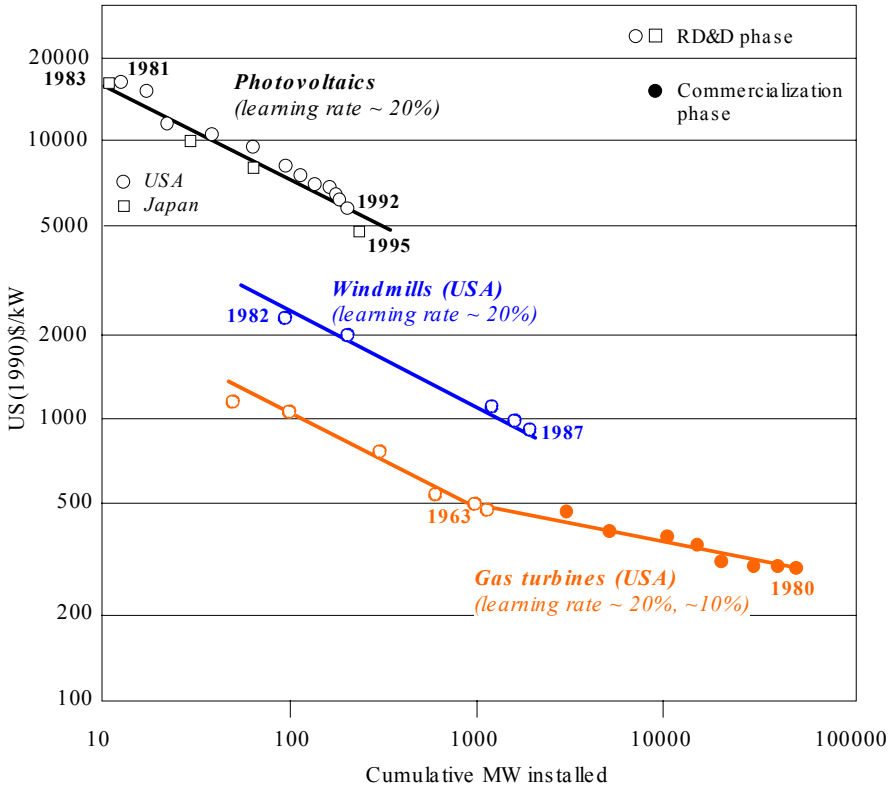
[134] Branscomb and Florida (1998) provide an excellent summary of these arguments (p. 30). The initial research on this was conducted by Arrow (1962) and Nelson (1959).

[135] Cited in Chertow 2000, p. 53

The failure to internalize environmental and security externalities and the need to overcome collective action problems provide important rationale for government involvement during the diffusion process. Examination of the process of technology diffusion, in general, and for energy technology, specifically, can further illuminate the role government must play in this process, which includes both R&D and market support after new technologies have first been introduced into the market. One useful way of depicting the diffusion of technologies is with experience curves, as shown in Figure 1. Experience curves represent a relationship between the cumulative production of a technology and its production cost. Analysis of numerous technologies since the 1970s suggest a logarithmic relationship in which for each doubling of production, cost decreases are generally within the range of 10 to 30 percent (Boston Consulting Group 1968, Argot and Epple 1990). Numerous studies suggest that this rate of cost decrease is typical for energy technologies as well, although outliers in both directions have been identified (Christianson 1995, McDonald and Schrattenholzer 2001).

Figure 1: Experience Curves for Photovoltaics, Wind Generators and Gas Turbines



Source: PCAST, Powerful Partnerships: The Federal Role in International Cooperation in Energy Innovation (1997), p. 3-7.

Behind this simple representation of an experience curve lies a complex set of activities that contribute to cost reduction, including: learning-by-doing, which can lead to reduced production costs; R&D investments that can lead to cost-reducing technological breakthroughs in products and process; and economies of scale (Grubler, Nakicenovic, and Victor 1999, Duke and Kammen 1999, Neij 1997). It is important to make the distinction between learning-by-doing and more formal R&D; the former occurs on the shop floor and through operational experience while the latter occurs through investments in new research and development. As will be discussed below based on examples of wind turbines, solar PV and gas turbines, for these energy technologies the learning process (and related cost decreases) has depended substantially on R&D investments. While learning-by-doing has been important, it has often suggested problems whose solution is found not on the shop floor, but rather in radical innovations in components or processing techniques. Furthermore, economies of scale alone have not been adequate to make PV cells or wind turbines cost-competitive. In sum, throughout the diffusion process that is depicted by experience curves, there are numerous innovation cycles – sometimes these are initiated by radical innovations in the core technology (e.g. new types of solar PV cells) and other times by radical innovations in components (e.g. variable speed drives in wind turbines). This ongoing process of innovation provides the rationale for government R&D investments.

Turning next to the demand-pull side of this process, for some technologies in the energy sector, the market for achieving economies of scale has depended substantially on government subsidies and regulations. The simple explanation for this is that because externalities are not reflected in energy prices, new energy technologies don't face a level playing field. This difficulty in creating a market for emerging energy technologies is compounded by the fact that energy (e.g. kilowatts and BTUs) is a commodity good, and thus most new technologies for providing energy services have limited niche markets. This is best understood by examining how new goods become competitive in the marketplace. Most new goods succeed in the private market by charging a premium to the lead adopters, who are willing to pay more for the good because of its improved quality over existing alternatives (Levinthal 1998). But for commodity goods such as energy, there are a limited number of consumers who are willing to pay extra based on how the good is produced. Thus it is difficult for new energy technologies to work their way down the experience curve simply within the confines of the private market. The exception to this is cases where there is a large enough niche market based on performance characteristics, for example, gas turbines' quick start-up and shutdown features that made them attractive for peaking markets when they were first introduced to the power sector in the 1960s.[136]

To complete this discussion, it is worth noting that government may also play a role in technology diffusion for technologies that are already cost-competitive in the private market. In cases where there is a public interest in greater deployment, as is the case for cleaner energy technologies, government may intervene in private markets to overcome high transaction costs or to close the gap between public and private discount rates (Jaffe and Stavins 1994). In these cases, investments in technology development are not primary, and are thus beyond the topic of this paper.

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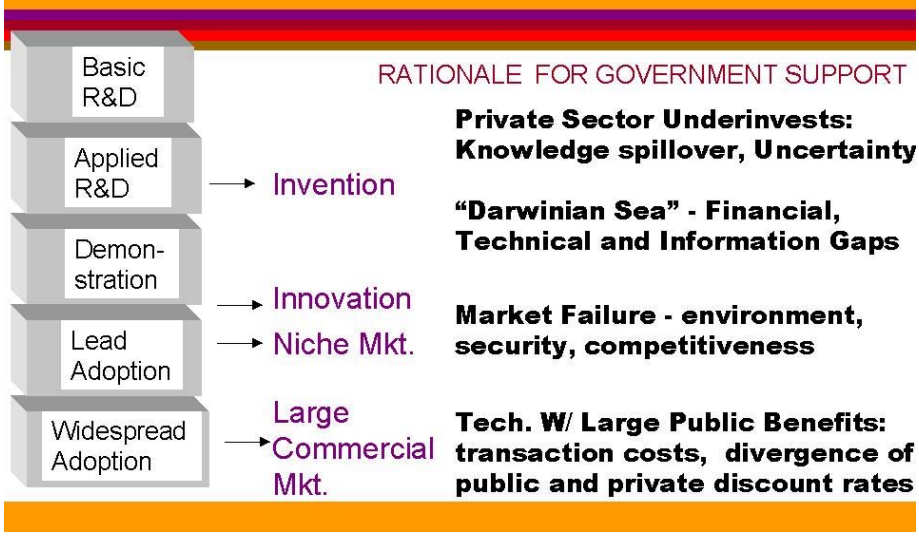
[136] For an in-depth exploration of the role and creation of niche markets for environmentally enhancing technologies, see Kemp, Schot, and Hoogma, 1998; Kemp, Rip and Schot, 1997.

Together these reasons, summarized in Figure 2, explain why government must take a broad role in technology innovation in the energy sector, a role even larger than the one taken in other sectors where innovation and diffusion can proceed through private market mechanisms once government has contributed to overcoming the underinvestment due to knowledge spillovers and the gaps between invention and innovation. For most commercial products, the private sector will make the necessary investments to drive a technology down the experience curve. For new technologies desired for their public rather than private good qualities, such as most cleaner energy technologies, successful commercialization depends on government support. As discussed in much greater depth below, the government's role will be most effective if it works synergistically, and often simultaneously, to support supply-push (e.g. R&D funding) and demand-pull (creation of markets through e.g. taxes and subsidies, regulation), and if applied R&D is undertaken through public-private partnerships.

Figure 2: Government Role Throughout the Process of Energy Technology Innovation



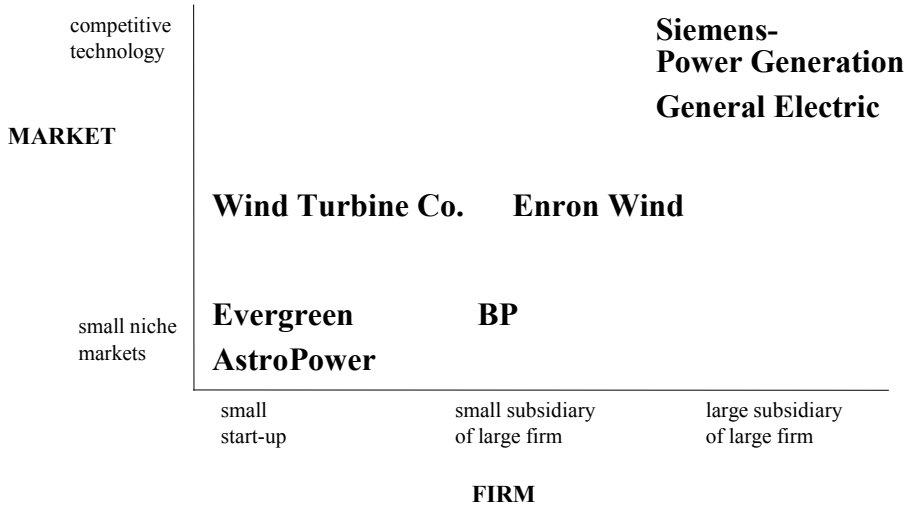
Long-Term Development of Power Technologies: Gas Turbines, Wind Turbines and Solar Photovoltaics

Examining the long-term histories of the policy and technological development of three technologies – gas turbines, wind turbines, and solar photovoltaics – provides a basis for further development of the concepts outlined above on the role of government in innovation for cleaner energy technologies. Our research focused largely on the United States, although it also included examining some of the policy history in Europe and Japan and interviews at two European firms. In undertaking this research, in addition to archival work and interviews with government personnel, we interviewed senior management and technical personnel in eight firms. This provided the opportunity to learn from the private sector how

government policy influenced strategic decisions about investments in technology innovation.

The firms that we studied varied along two key dimensions: firm size and stage of technology development, with the latter factor changing over the 30-year time-span of this study. Their state in 2001 is depicted graphically in Figure 3. For gas turbine firms, we interviewed Siemens-Westinghouse Power Generation and General Electric Power Company. These are both large subsidiaries of large firms. Throughout the period of this study, gas turbine technology was competitive in the marketplace, and the firms were engaged in ongoing incremental innovation and radical component innovation. The two wind turbine companies we studied were Enron Wind Corp. (formerly Zond, Inc. and now General Electric Wind Corp.) and The Wind Turbine Company. The first started out as a small firm and later became a small subsidiary of a large firm; the second is a small start-up firm. Enron Wind Corp. made incremental product and process innovations and radical component innovations to an established wind turbine design. The Wind Turbine Company is attempting a radical innovation in wind turbine design. We interviewed four firms in the solar PV industry. Two of the firms, BP Solar and Siemens Solar, are small subsidiaries of large firms. The other two firms, Evergreen Solar and Astro Power, are small startups. In the solar case, these firms represented the full spectrum of innovative activity, focusing both on R&D for new types of solar cells as well as improvements to existing technologies. Their activities included radical and incremental innovations in both products and processes.

Figure 3: Case Studies of Solar PV, Wind Turbines and Gas Turbines



Although the length of this paper prohibits in-depth discussion of these cases, we present some details about two aspects of these cases in order to more completely illustrate our findings. First, an abbreviated history of wind turbine development is presented in order to highlight the interplay and importance of government activities in supply-push and demand-pull throughout the process of innovation. After presenting this example, the paper then turns to lessons on integrating supply-push and demand-pull mechanisms that are garnered not only from the wind case, but also across the three cases. The paper then briefly discusses three public-private R&D partnerships that supported the development of solar PV and gas turbines during the 1990s, and presents lessons on the characteristics of R&D partnerships that contribute to effectiveness. [137]

Supply and Demand Working Synergistically: U.S. Wind Turbine Policy

The U.S. has experienced two periods of rapidly expanding deployment of wind turbines - the first in the 1980s, the second in the late 1990s and continuing into the new millennium. The 1980s expansion was based largely in California, where installed capacity for grid-connected wind generation grew from less than 10 MW in 1980 to 1525 MW by 1990. During this period there was a fivefold decrease in the cost of wind-generated electricity, from 38 cents/kWh in 1980 to 8 cents/kWh in 1990. The second significant expansion in wind-generated electricity took place in numerous states, with installed capacity increasing to over 4000 MW by the end of 2001, and prices falling to 4 cents/kWh.[138] The policies that supported this successful development are summarized in Figure 4, and discussed in more detail below.

The U.S. federal and state governments enacted a variety of policies that supported wind turbine development and deployment during the 1970s and 1980s.[139] In terms of supply-push, the U.S. federal government took two approaches to sponsored R&D. The first was a "big science" approach, with the aim of developing large turbines for grid-connected electricity generation. This program was largely a failure and did not result in commercial turbines. The second approach to R&D was practice driven, focusing on component innovation for somewhat smaller turbines, again aimed at the grid-connected market. It looked to the challenges faced by wind turbines in operation to define the research agenda for component innovation. This program was a success, contributing substantially to improvements in wind turbine efficiency during the 1980s. Of the 12 key innovations in wind turbine components, seven relied on partial or total public funding (Loiter and Norberg-Bohm 1999).

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[137] More detailed discussions of these cases are available: for the solar case see Margolis 2002; for the wind case see Loiter and Norberg-Bohm 1999, for the gas turbine case, see Unger and Herzog 1998, Watson 1997, and Norberg-Bohm 2000; for a comparison across the cases through the mid-1990s, see Norberg-Bohm 2000.

[138] This data comes from the American Wind Energy Association (AWEA) website. Http: www.awea.org/faq. Assumptions for price calculations are: levelized costs at excellent wind sites; large project areas, not including the production tax credit (post 1994). Costs are of course difficult to calculate given the numerous factors that determine costs. The California Energy Commission data shows a fivefold decrease in the cost from 1980 to 1995, with cost going from 25 cents/kWh to 5 cents/kWh. All costs are in current dollars. The installed capacity data is from the U.S. Department of Energy Wind Energy Program and AWEA. The 2001 data is based on project completion data reported by developers. The installed capacity for 2000 was 2.554

[139] This summary for the 1970s and 1980s is drawn from Norberg-Bohm, 2000.

Figure 4: Government Policy for Wind Turbine Development

	Supply-	Demand-
1980	• MOD big-turbine R&D Program • Rocky Flats/SERI subsystem and small-turbine R&D program	• PURPA – liberal avoided costs – long term purchase contracts • Federal and state tax credits • Wind resource assessments
1990	• Advanced Wind Turbine Program – Near-Term Product Development – Value Engineered Turbine – Next Generation Product Development • Phase I- concept development • Phase II-product development • Turbine Development Supporting R&D	• EPACT- 1.5cents/kWh tax credit • DOE- EPRI Utility Wind Turbine Performance Verification Program • State requirements for wind power/renewables

Wind generated electricity was more expensive than alternatives throughout this period. A combination of federal and state policies together provided the incentives that created demand. At the federal level, the government offered tax credits and also passed the Public Utilities Regulatory Policy Act (PURPA), which required that utilities buy-back power from some small and renewable generators at avoided costs. PURPA was implemented at the state-level. California's implementation of PURPA included generous avoided costs and equally important, long-term purchase contracts. California also passed state-level tax credits and sponsored a wind resource assessment that identified the best sites for wind installations. Together these state and federal policies created a market for wind turbines.

During this first period, the synergism of these supply and demand mechanisms was crucial for the rapid technological development of wind turbines. Government support for radical component innovation was necessary – the market was too immature and too insecure to attract significant private funding for R&D. Experience with installed wind farms not only helped guide government R&D efforts, but the emerging market also led to incremental innovation by turbine manufacturers, not only in design, but also in maintenance and siting practices. Unfortunately, the demand-pull policies of the first wind expansion were too short-lived to create a lasting industry. They only acted in concert and strongly over a short period of time. With the elimination of long-term contracts in 1985 and California tax credits in 1987, the market for new wind turbines dried up and the existing U.S. manufacturers did not survive this downturn in the market.

After a hiatus of policy stimuli in the late 1980s, new supply-push and demand-pull policies were enacted in the 1990s. The National Renewable Energy Laboratory (NREL) continued R&D programs for turbine development, including component design, design codes, design review, and testing. NREL also embarked on an Advanced Wind Turbine Program (AWT) that included three phases: (1) Concept Design Studies; (2) Near-Term Product Development

(NTPV) and Valued Engineered Turbines (VET); and (3) Next Generation Product Development (NGPD). The goal of these programs was to reduce the cost of wind-generated electricity, so that it would be competitive in the U.S. market. Phase 2 had a goal of producing wind-generated electricity at 5 cents/kWh from 13 mph sites; the phase 3 goal was 2.5 cents/kWh at 15 mph cites, a price considered competitive with fossil fuel base-load units (Magliore and Calvert).

When the Advanced Wind Turbine Program was launched, it focused on the development of innovative wind turbine configurations. Many in the wind industry criticized NREL for only supporting innovative turbine configurations, when the basic Danish design (horizontal axis, three blade, up-wing configuration) was a proven success. Several U.S. wind farm developers were anxious to have a role in wind turbine development (Cadogan 1999). These wind farm developers wanted to draw on their experience of operating and maintaining wind turbines, almost exclusively of the Danish design, in order to launch into the wind turbine manufacturing business. Thus, in the second and third phases of the AWT, NREL opened its solicitations to improvements in the Danish design as well as to innovative configurations.

Demand-pull mechanisms started slowly but picked up as the decade proceeded. The 1992 Energy Policy Act provided a 1.5 cents/kWh tax credit for wind-generated electricity.[140] This provided important support, but was not enough to make wind turbines cost competitive. Given the dismal market for wind turbines during the early 1990s, NREL was looking for additional ways to support the deployment of the new generation of U.S. manufactured wind turbines that were being developed with support from the NREL R&D programs. In 1992, NREL and EPRI joined forces to launch the Utility Wind Turbine Performance Verification Program (Moore 1999, DOE 1998, DOE 1999). This program provided cost-sharing and technical assistance for the deployment of new commercial wind turbines in distributed applications. Although small, eventually resulting in 4 utility installations of 6 MW or less, the program provided a timely stimulus, as it was announced and initial contracts vetted in the first half of the decade, before an increase in wind-support policies by the states. This allowed firms, and Zond, Inc. in particular (as will be discussed below) to test and improve the performance of new turbine designs, and utilities in different parts of the country to learn about the needs of operating in climates outside California (Moore 1999, DOE 1998).

In the second half of the decade, state-level policies in support of wind expanded rapidly. The first commercial U.S. wind turbine developments of the decade were the result of mandates in two states for utilities to generate electricity from wind or renewables. Northern States Power in Minnesota made a commitment to 425 megawatts of wind energy by 2002 in exchange for permission to expand its nuclear-waste storage facilities and MidAmerican Energy finally agreed to stop court proceedings and implement a requirement, enacted by the Iowa legislature in 1983, to generate a small percentage of electricity from renewables (Parsons 1998, Moore 1999). As the decade proceeded, as part of their electric power sector deregulation, a number of states enacted policies to support renewables, either through renewable portfolio standards or systems benefit funds. It is important to note that despite

[140] With adjustment for inflation, the tax credit was 1.7 cents/kWh in 2001. The tax credit expired at the end of FY 2001, although there is hope it will be retroactively passed for FY 2002 and beyond in upcoming energy legislation .

declines in the cost of wind-generated electricity, new wind turbine developments were only being built in states that provided additional incentives beyond the 1.5 cents/kWh federal tax break. In other words, by the end the century, wind-generated electricity was still not cost-competitive with the least expensive fossil alternatives and additional state-level policies determined the viability of wind-turbine projects (Parsons 1998).[141]

Understanding how supply-push and demand-pull worked synergistically during this decade is best viewed through the experience of Enron Wind Corp., the only U.S. wind turbine manufacturer at the end of the century. Zond, Inc., the predecessor to Enron Wind Corp., was a successful wind farm developer in California during the 1980s. This production experience laid the groundwork for Zond's decision to become a turbine manufacturer, as Zond's operation and maintenance of the Danish wind turbines provided basic technical capability for moving into manufacturing. To implement this decision, Zond turned to DOE for R&D support. During the 1990s, DOE funded about one-third to one-half of the technology development at Zond/Enron Wind Corp. Through a 1994 contract for the Value Engineered Turbine Development Program (Phase II of the AWT), NREL provided important resources, both financial and technical, that contributed to the development of Zond's first commercial turbine, the Z-40 (550kw).[142] The NREL/EPRI Utility Wind Turbine Performance Certification Program provided the first market for the Z-40. A Next Generation Product Development (AWT Phase III) concept development contract allowed Zond to move forward on its next turbine, the Z-46 (750kw) in a timely fashion. This in turn made it possible for Zond to bid this turbine for the Northern States Power solicitation, the first new large wind turbine development in the U.S. in almost a decade. Enron Wind Corp. went on to win several of the new wind farm solicitations, developments that were taking place because of state-level market support policies. In sum, the R&D funding and market creation policies resulted in a business success that neither would have achieved by itself.

Although wind generated electricity is still not quite cost-competitive with the alternatives in most U.S. markets, this history demonstrates how supply and demand can act synergistically to foster technology innovation that is environmentally enhancing, bringing a technology through the learning process necessary to improve performance and decrease cost. It also demonstrates that the industry will die-out if this support is withdrawn before the technology is competitive in the private market. Furthermore, these efforts resulted in one internationally competitive U.S. wind turbine manufacturer, one U.S. start-up firm with an innovative turbine design, and several overseas firms building manufacturing facilities in the United States. Technological progress is continuing, and the industry projects that wind-generated electricity can be competitive with alternative sources of electricity by 2005.[143]

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[141] This may not remain true, at least not in all markets. For example, the spike in the price of electricity in some parts of the country, and in natural gas throughout the country during the 2000 - 2001 period may have changed this result.

[142] Dr. Amir Mikhail, vice-president of engineering at Zond, is quoted as saying, "The turbine verification program has been very valuable for us. It allowed us to move quickly from a prototype unit into full production. At the same time, we've been able to see how our machine operates in different environments." (DOE 1997, p. 7)

[143] The AWEA projects costs of 2.5 to 3.5 cents/kWh by 2005. http://www.awea.org/faq/cost.html.

Lessons: The Interaction of Government Support for Supply-Push and Demand-Pull

Although this paper only profiles wind turbines, our examination of all three technologies makes an even stronger case for the central thesis of this paper, which has two components. First, in order to bring new energy technologies through commercialization government must support R&D throughout the process of innovation, not only during invention and the development of initial prototypes, but also during commercialization. Second, success depends on the simultaneous use of supply-push and demand-pull mechanisms.

Starting with government support for R&D, DOE funding has played an irreplaceable role in catalyzing private sector investment for bringing technologies from concept through commercialization. For all of the firms in our study, the government contribution to the research budget for the specific technology projects we examined was 33 percent or greater. In many cases, particularly for smaller firms, it was much greater. Furthermore, private funding was often contingent on receiving government contracts. This was true both for private funding from a parent corporation, from within a subsidiary, and from private venture capitalists. In several cases, government funding helped firms reach the milestones that were necessary to raise successive rounds of private funding.

It is worth highlighting that DOE R&D funding was critical to advance technological development not only in start-up and small firms, but in larger firms as well. Furthermore, public funding was important not only for emerging technologies, but also for stimulating innovation in more mature technologies. Turning back to our discussion of the rationale for government intervention, financial strength does not translate into innovation for the public good, and therefore even financially strong firms may not focus their innovative efforts in areas where they cannot easily capture a private market. Second, the financial strength of the parent company does not necessarily translate into financial commitments to a specific technology or financial strength of a subsidiary. Third, component innovation for mature technologies may be too risky for the private sector. Finally, for an established technology, a lull in the market reduces the ability to generate internal R&D funding.

Several facts emerged that underlined the need for market support policies as well. First, small and uncertain niche markets limit the ability of firms to generate internal funds for ongoing R&D. Although private firms and private funders expressed cautiousness about government created niche markets (i.e. markets created by government regulations and subsidies), the history of the last 30 years suggests that the private sector responds quite strongly if the incentives are provided over a relatively long time frame. The two periods of wind turbine development are an excellent example of this. On the other hand, strong private niche markets can eliminate the need for government market support programs, as was the case when gas turbines were first deployed in the power sector in the 1960s. Finally, institutional arrangements can enable or block niche formation. The passage of the Public Utilities Regulatory Policy Act (PURPA) and current regulatory reform demonstrate the ability for changes in utility sector regulation to provide opportunities for new technologies.

Public-Private Partnerships in Gas Turbines and Solar Photovoltaics

In addition to examining the need for government support of R&D, these cases also gave us an opportunity to examine the organization of government R&D programs through in-depth studies of three public-private R&D partnerships: the Advanced Turbine Systems (ATS) program, the Photovoltaic Manufacturing Technology (PVMaT) project, and the Thin-Film PV Partnership project. These three programs have each been evaluated as quite effective in reaching near- to medium-term technological goals.[144]

The ATS program was launched in 1992 with the goals of developing ultra-high efficient, super-clean, and cost-competitive gas turbines. The ATS was a 9-year research, development and demonstration program with a total budget of $826 million of which $325 million ($1999) was industry cost-share.[145] It involved development of utility-scale turbines (approximately 400 MW and larger), industrial-scale turbines (5-15 MW), and technology base development for materials and manufacturing, combustion, and coal and biomass applications. The goals for utility scale turbines were efficiency greater than 60%, NOx emissions of less than 10 ppm, and electricity cost decrease of 10% compared to existing turbines. The industrial scale turbines had the goals of a 15% improvement in fuel efficiency, a 10% reduction in NOx emissions and a 10% reduction in the cost of electricity. The ATS program has been quite successful. General Electric has completed testing and begun demonstrations of its ATS turbine. Siemens-Westinghouse is in the process of field-testing and will conduct demonstrations in 2002 (DOE FETC, 1999a, 1999b). Industrial scale ATS turbines are also currently being tested, and Solar Turbines expects to begin commercialization in 2003 (NRC 2001). Furthermore, many of the ATS innovations have been integrated into existing turbines (Layne 2000).

The Photovoltaic Manufacturing Technology (PVMaT) project, which began in 1991, had the goal of ensuring "that the U.S. [PV] industry retains and extends its world leadership role in the manufacture and commercial development of PV components and systems" (Witt, et al. 1993). In order to meet this goal, the project has focused on improving manufacturing processes and equipment, accelerating manufacturing cost reductions, improving commercial product performance and reliability, and laying the groundwork for substantial scale-up of U.S. based PV manufacturing plant capacities (Witt, et al. 1998). Although originally designed as a 5-year program, it has continued for the past decade. Total project funding through FY1999 was $80.5 million in DOE funding and $59.1 million in industry funding (Witt, et al. 1999). PVMaT played an important role in helping U.S. PV manufacturers remain competitive in the rapidly growing global PV market of the 1990s. For participating firms, the weighted-average cost for manufacturing PV modules declined by 36% over this period (Witt, et al. 2000).

The Thin-Film PV Partnership, formally organized between 1992 and 1994, focuses on further development of thin-film PV technologies including amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium diselenide (CIS). Total funding under the

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[144] The program summaries below are from Norberg-Bohm and Margolis 2001.

[145] This data is from NRC 2001. The NRC report examines the industrial and utility-scale turbines separately; this is simply a compilation of the two budgets presented in the report.

thin-film PV partnership project between 1994 and 1999 was $102 million in DOE funding and $30 million in industry funding. The majority of project funding is for cost-shared contracts with companies that are working to bring thin-film technologies from the prototype to pilot production phase of development. It also funds R&D at NREL, universities, and firms aimed at solving more fundamental problems. A key feature of the Thin-Film PV Partnership is its team structure, with three national teams organized around specific technologies (a-Si, CIS, and CdTe), and a fourth team focused on the potential environmental impacts of PV. The Thin-Film PV Partnership has contributed to increases in the efficiency of both laboratory cells and large-area modules, and has helped firms move technologies from the lab to pilot production (NREL 2000a, NREL 2000b).

Lessons: Effective Public-Private Partnerships

Several lessons on how to effectively organize public-private R&D partnerships emerged from our evaluation, as well as that of others (Mowery 1998, NRC 2001).[146] The first set of lessons deal with goal setting in relationship to the status of technology and markets. The second set examines the role of industry in public-private partnerships. The third looks at the engagement of other parties in the technology development process.

Public-private partnerships create an opportunity to set "stretch," but reachable goals for technology development. Government involvement and financial support for R&D partnerships provides an opportunity for government to push industry toward technological developments that create public benefits, for example environmental protection, beyond where industry would have gone without the public-private partnership. Nonetheless, these partnerships must base technological goals on a clear understanding of market potential, so that there is a reasonable chance that there will be a market for the technology if the program goals are met. This is particularly important for public-private R&D partnerships aimed at moving technologies into the marketplace. Furthermore, the program should have periodic revaluation of its goals and an ability to readjust goals mid-stream, both in light of the pace of technological developments and in changes in the marketplace that could affect the attractiveness of the technology, which may include factor prices, developments in competing technologies, and regulatory changes.

The effectiveness of these programs depended in large part on the effective engagement of industry leadership throughout the process, from goal setting through implementation. Industry was involved in deliberations about appropriate goals, and then took the leadership in defining an R&D strategy for reaching these goals. The partnerships were based on cost sharing, with firms retaining the right to IPR developed in the program. The cost sharing increased as technologies got closer to commercialization, ranging from 10% during concept development to 40% to 70% for final stages of development and demonstration. Cost-sharing and long-term commitments, which are difficult to insure for both government and

[146]In particular, the NRC (2001), which examined the ATS project and other DOE public-private partnerships in energy efficiency and fossil energy, reached the following conclusions, that are quite similar to our investigation: R&D portfolios should focus first on public good goals, public-private cost-sharing is an effective strategy, technology for rapid deployment needs to be consistent with the economic incentives of users, and programs should strive for flexibility and include targets and milestones for deciding whether to continue.

firms, along with the transfer of intellectual property rights, were key elements in the successful engagement of industry in these partnerships. Engaging business units and not only R&D departments was also an important design element.

The success of these partnerships also depended on effectively engaging a number of parties other than firms and the Department of Energy. First, goal setting was most successful if it involved a range of stakeholders, not just industry and government. In this way, it was better able to assess all of the factors affecting technology development and the market for the technology. Second, universities contributed to these programs through technological breakthroughs and the development of future employees. Universities were effectively engaged in these programs by having the university research agenda defined by industry and focused on riskier or longer-term R&D that industry would not undertake on its own. Several different organizational structures were developed to ensure that some funding was earmarked for university research. These programs also successfully engaged national labs in providing complementary assets such as testing facilities that did not exist in the private sector, would not be built by single firms, or were not available to small firms. In some instances, the national labs also provided skilled researchers. Finally, in all these programs regular meetings, on at least in annual basis, provided important networking opportunities for the participants.

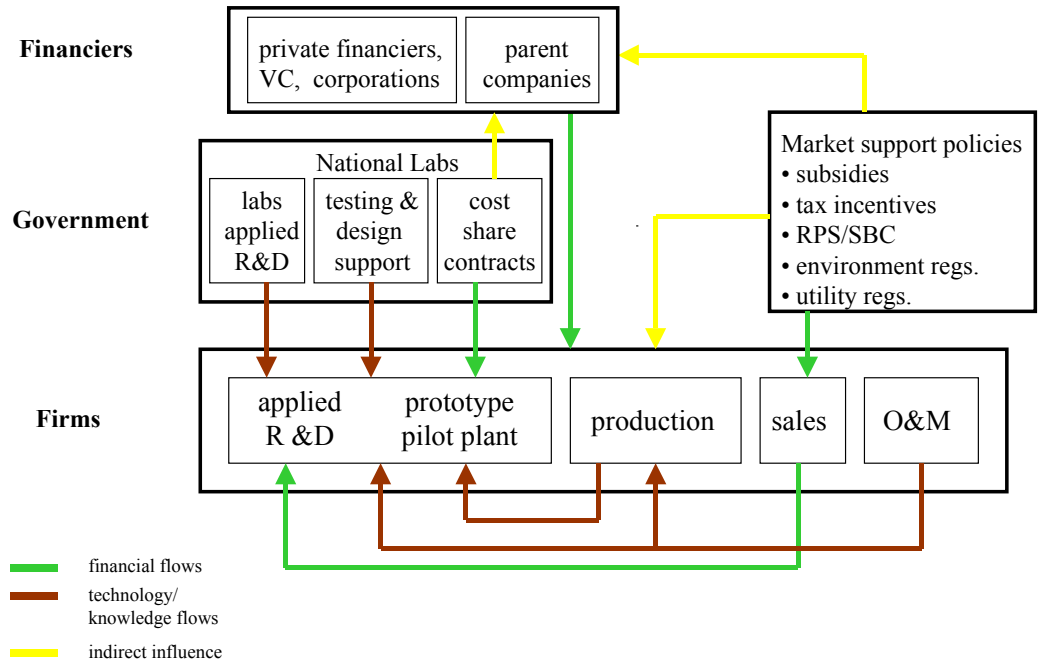
In sum, the types of public-private R&D partnerships that were examined through this project were quite effective. They can serve as a model for government involvement in efforts to bring technologies "down the experience curve." Public-private partnerships may also be an important approach for longer-term applied research, but they would likely have some differences in the approach to goal setting and setting of research agendas, as it would make sense for industry to be less dominant in this process.

Conclusion

This paper demonstrates that a virtuous cycle can be created by the coordinated use of supply-push and demand-pull policies, as illustrated in Figure 5.[147] For many other commercial products, this virtuous cycle takes place with little or no direct government intervention during the diffusion process. Because government must be involved in the diffusion process for emerging energy technologies, it is essential that government and industry work together through public-private partnerships, in both planning and implementation of R&D programs. Fortunately, government can expect to provide decreasing support over time. Industry can, and should be expected, to fund an increasing share of R&D as innovations move closer to commercialization, and as the product moves closer to being commercially competitive. Equally important, government must design its market support mechanisms in a way that subsidies decrease as the product gets closer to a competitive price.

[147] Watanabe (2000) discussed the concept of a virtuous cycle in relationship to PV development in Japan. His article focuses on the way that R&D investments create this virtual cycle. Although his conclusion highlights the importance of "developing market reward structures," the analysis in the paper does not explore the government created market support programs that were also a key element in the Japanese virtual cycle.

Figure 5: The Virtuous Cycle: Simultaneous Support For R&D And Market Creation



Source: Norberg-Bohm and Margolis, "The Government's Role in Filling the Gap for the Commercialization of New Energy Technologies," AAAS Annual Meeting, Feb. 19, 2001

Despite the consistency of the message above, both from a theoretical standpoint and through our case analysis, many factors influence the level and role that government needs to play for successful commercialization of emerging energy technologies. These include: (1) additional sources of technology innovation, which may include government research in defense and other non-energy agencies and private sector research for related products; (2) the size, certainty and longevity of private niche markets for a technology; and (3) and the financial and technological capability of the private sector (Norberg-Bohm 2000).

It is also critical to consider the timing and coordination of the disparate government actions. For example, it does not make sense to create large and expensive market support mechanisms if fundamental technological breakthroughs will be necessary to make a technology cost-competitive. In this case, smaller subsidies for niche markets may be adequate to foster learning-by-doing and to support private firms while further R&D efforts take place. In contrast, for technologies that can become cost-competitive through learning-by-doing and economies of scale, market support may be adequate. In sum, a wise program is technology specific, and depends on the stage of technology and market development. Thus, effective policy must be based on a careful assessment of the state of the technology and market for specific technologies, with periodic reassessment.

The message in this paper is one that DOE cannot implement on its own. Certainly many of the lessons for R&D can and are already being followed by DOE and the national laboratories. On the market creation side, DOE's role is important, but more limited. DOE can in some instances contribute to market creation through programs that overcome informational barriers to deployment or provide subsidies for demonstration and deployment. Perhaps more importantly, DOE and the national laboratories have the capacity to undertake the analysis that supports policy development for deployment, and policy development for coordination of supply-push and demand-pull mechanisms.

In sum, the message of this paper is directed beyond DOE, and toward national energy policy. Our national energy policy should focus on the longer-term, recognizing the need to foster the development and diffusion of a range of new energy technologies in order to provide environmental protection, national security and economic competitiveness. And to accomplish this successfully, national energy policy must develop a well-orchestrated policy of supply-push and demand-pull approaches.

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Appendix A: Authors' Biographies

Dr. John Alic, a staff member of the congressional Office of Technology Assessment from 1979 to1995, consults on public policy issues related to technology and science. At OTA, he directed assessments beginning with U.S. Industrial Competitiveness: A Comparison of Steel, Electronics, and Automobiles, which appeared in 1981. Alic is co-author, with Lewis Branscomb, Harvey Brooks, Ashton Carter, and Gerald Epstein, of Beyond Spinoff: Military and Commercial Technologies in a Changing World, published in 1992. New Rules for a New Economy: Employment and Opportunity in Postindustrial America, a Century Foundation book co-authored with Stephen Herzenberg and Howard Wial, appeared in 1998. In recent years, Alic has consulted for several government agencies, the National Academy of Engineering, and the H. John Heinz III Center for Science, Economics, and the Environment, among other organizations.

Prof. Ashish Arora has a Ph.D. in Economics from Stanford University and is Associate Professor of Economics and Public Policy at Carnegie Mellon University, Pittsburgh, and currently visiting at the Department of Economics, Stanford University. Professor Arora's research focuses on the economics of technological change, the management of technology, intellectual property rights, and technology licensing. He has in the past worked on the international technology transfer, and on the productivity of university research in biotechnology and economics. He has published extensively on the growth and development of biotechnology and the chemical industry, including a co-edited volume on the chemical industry, *Chemicals and Long Term Economic Growth*, published by John Wiley and Sons, 1998. He has recently concluded a Sloan Foundation sponsored study of the Indian software industry and its links to the U.S. economy. His most recent book, *Markets for Technology*, has recently been published by MIT Press. He is the research director for the Software Industry Center at Carnegie Mellon University.

Dr. Philip Auerswald is an Adjunct Lecturer and Assistant Director of the Science, Technology, and Public Policy program at the Kennedy School of Government. His research pertains to industrial organization and the economics of technological innovation. He holds Ph.D. in Economics from the University of Washington and a B.A. in Political Science from Yale. With Lewis Branscomb he is the co-author of *Taking Technical Risks: How Innovators, Executives and Investors Manage High Tech Risks* (MIT Press, 2001). He has been a consultant to the Commonwealth of Massachusetts' Department of Economic Development, and is principal author of *Competitive Imperatives for the Commonwealth: A conceptual framework to guide the design of state economic strategy.*

Prof. Lewis M. Branscomb is the Aetna Professor of Public Policy and Corporate Management Emeritus and Emeritus Director of the Science, Technology and Public Policy Program in the Belfer Center for Science and International Affairs at Harvard University's Kennedy School of Government. He is Principal Investigator of the Harvard Information Infrastructure Project and other projects in Technology Policy in the Center. His recent research has produced books that focus on evaluating and redirecting the Clinton-Gore technology policy with James Keller, on state government science and technology with Megan Jones and David Guston, on Korean technology policy with Young-Hwan Choi, and intelligent transportation systems with James Keller. A research physicist at the U.S. National Bureau of Standards (now the National Institute of Standards and Technology) from 1951 to 1969, he was Director of NBS from 1969 to 1972. In 1972, Dr. Branscomb was named Vice President and Chief Scientist of IBM Corporation, serving until his retirement from IBM in 1986. He has served national and state governments in a number of appointed advisory capacities. He is a member of the National Academy of Engineering, the National Academy of Sciences and a member of the Academy's Council, and the National Academy of Public Administration.

Dr. Calestous Juma is Director of the Science, Technology and Innovation Program at Center for International Development at Harvard University and Senior Research Fellow at the Belfer Center for Science and International Affairs at Harvard University. He is former Executive Secretary of the United Nations Convention on Biological Diversity and founding Executive Director of the African Centre for Technology Studies in Nairobi (Kenya), an independent public policy research institution. He has won several international awards, including the Pew Scholars Award in Conservation and the Environment (1991), the United Nations Global 500 Award (1991) and the Henry Shaw Medal (2001). He holds a Ph.D. in Science and Technology Policy Studies from the Science Policy Research Unit at the University of Sussex (UK) and has worked as a teacher, science writer, chief executive officer and advisor.

He is Visiting Professor at the University of Strathclyde (UK), Member of the Kenya National Academy of Sciences, Fellow of the World Academy of Arts and Sciences, Fellow of the New York Academy of Sciences, Member of the U.S. National Research Council's Board on Agriculture and Natural Resources and its Committee on Agricultural Biotechnology, Health and the Environment. He is Associate Editor of the *International Journal of Biotechnology*, *International Journal of Environmental Technology and Management*, *International Journal of Global Environmental Issues*, *International Journal of Technology and Management*, and *International Journal of Technology Transfer and Commercialization.*

Prof. David Mowery is Milton W. Terrill Professor of Business and Public Policy in the Walter A. Haas School of Business at the University of California, Berkeley and the Director of the Haas School's Ph.D. program. He received his undergraduate and Ph.D. degrees in economics from Stanford University and was a postdoctoral fellow at the Harvard Business School. Dr. Mowery taught at Carnegie-Mellon University, served as the Study Director for the Panel on Technology and Employment of the National Academy of Sciences, and served in the Office of the United States Trade Representative as a Council on Foreign Relations International Affairs Fellow. He has been a member of a number of National Research Council panels, including those on the Competitive Status of the U.S. Civil Aviation Industry, on the Causes and Consequences of the Internationalization of U.S. Manufacturing, on the Federal Role in Civilian Technology Development, on U.S. Strategies for the Children's Vaccine Initiative, and on Applications of Biotechnology to Contraceptive Research and Development. His research deals with the economics of technological innovation and with the effects of public policies on innovation; he has testified before Congressional committees and served as an adviser for the Organization for Economic Cooperation and Development, various federal agencies and industrial firms. Dr. Mowery has published numerous academic papers and has written or edited a number of books, including *Paths of Innovation*; *U.S. Industry in 2000*; *The Sources of Industrial Leadership*; *The International Computer Software Industry: A Comparative Study of Industry Evolution and Structure; Science and Technology Policy in Interdependent Economies; Technology and the Pursuit of Economic Growth; Alliance Politics and Economics: Multinational Joint Ventures in Commercial Aircraft; Technology and Employment: Innovation and Growth in the U.S. Economy; The Impact of Technological Change on Employment and Economic Growth; Technology and the Wealth of Nations; and International Collaborative Ventures in U.S._Manufacturing.* His academic awards include the Raymond Vernon Prize from the Association for Public Policy Analysis and Management, the Economic History Association's Fritz Redlich Prize, and the *Business History Review's* Newcomen Prize.

Dr. Vicki Norberg-Bohm is the Director of the Energy Technology Innovation Project (ETIP) at BCSIA. ETIP focuses on the policies and institutional changes needed to develop and deploy a new generation of energy technologies that can address the multi-faceted challenges in the energy sector, including environment, development and security. She is currently leading two research projects: Technology Innovation for Global Change: The Role of R&D, Regulation and Assessment, which focuses on lessons for policy design from 3 energy technologies – gas turbines, wind turbines, and solar photovoltaics; and Voluntary, Collaborative and Information-based approaches to reaching energy and environmental goals, which examines the effectiveness of this new set of policy mechanisms. Prior to joining the Belfer Center, Dr. Norberg-Bohm was an assistant professor in the Department of Urban Studies and Planning at MIT. While at MIT, she was co-PI of the Environmental Technology and Public Policy Program, and part of the research team on "Creating Incentives for Environmentally Enhancing Technological Change" at MIT's Center for Environmental Initiatives. From 1998 -1999, she was also co-Director of the Program for Environmental Education and Research, which focused on developing multidisciplinary educational initiatives. She has a Ph.D. in Public Policy from Harvard University. Prior to returning to school to pursue a Ph.D., she was a practicing engineer in the area of energy and environmental systems. She has a M.S./ B.S. in Mechanical Engineering from Washington University in St. Louis.

Appendix B: Workshop Agenda

The Energy Technology Innovation Project
Belfer Center for Science and International Affairs
Kennedy School of Government
Harvard University

presents

The Government's Role in Technology Innovation:
Development of Insights for Power Technologies

sponsored by

The Office of Power Technologies
Office of Energy Efficiency and Renewable Technologies
The U.S. Department of Energy
and the National Renewable Energy Laboratory

Feb. 11, 2002
Carnegie Endowment, Washington D.C.
1779 Massachusetts Avenue NW

Final Agenda

8:30 - 9:00	Continental Breakfast
9:00	**Welcome** Mr. David K. Garman, Assistant Secretary for Energy Efficiency and Renewable Energy, DOE
9:15 - 10:15	**Panel 1: The Government's Role in Technology Innovation: Crosscutting Issues** Chair: Dr. Abe Haspel, Deputy Assistant Secretary, Office of Planning, Budget and Management, Office of Energy Efficiency and Renewable Energy, DOE *Policies for Innovation: Learning from the Past* Dr. John Alic, consultant, formerly Office of Technology Assessment, Congress of the United States *The Transition from Invention to Innovation: Sources and Flows of Public and Private Finance* Prof. Lewis Branscomb, Harvard University Discussants: Dr. Peter Bihuniak, BP Solar Former Congressman Robert Walker, The Wexler Group

10:15 - 10:45	**Discussion of Panel 1**
10:45 - 11:00	Break
11:00 - 12:00	**Panel 2: The Government's Role in Technology Innovation: A Sectoral Analysis (part 1)** Chair: Dr. Stanley Bull, Associate Director, National Renewable Energy Laboratory *Electronics, Computers, and the Internet* Prof. David Mowery, University of California, Berkeley *Biotechnology* Dr. Calestous Juma, Harvard University Discussants: Mr. Brent Erickson, Vice President, Industrial and Environmental, Biotech Industry Organization Dr. John Gibbons, former Assistant to the President, Director of the Office of Science and Technology Policy, The White House
12:00 - 12:30	**Discussion of Panel 2**
12:30 - 1:30	Lunch
1:30 - 2:30	**Panel 3: The Government's Role in Technology Innovation: A Sectoral Analysis (part 2)** Chair: Dr. Robert Dixon, Deputy Assistant Secretary, Office of Power Technologies, Office of Energy Efficiency and Renewable Energy, DOE *Chemical Industry* Prof. Ashish Arora, Carnegie Mellon University *Energy (Power) Technologies* Dr. Vicki Norberg-Bohm, Harvard University Discussants: Former Congressman Philip Sharp, Van Ness Feldman, P.C. & Harvard University Mr. T.J. Glauthier, Electric Power Research Institute
2:30 - 3:30	**Discussion of Panel 3**
3:00 - 4:00	Closing Discussion: Lessons for Future Policy Rapporteur: Prof. David Hart, Harvard University