Policy Issues for R&D Investment in a Knowledge-Based Economy

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ABSTRACT. The "Internet Revolution" induced an unbalanced perspective on future economic growth strategies. Because information technology (IT) largely constitutes an infrastructure upon which other economic activity is based, its economic role is to facilitate the productivity of investment in a wide range of products and services that meet final demand. Other economies around the world can and are investing in the same infrastructure, so the efficiency advantages now being realized by the U.S. economy will be fleeting unless U.S. R&D efforts produce a new and broad range of innovative products and services that take advantage of this infrastructure.

A deep and diverse technology-based manufacturing sector must be a core objective of a national R&D strategy. United States' manufacturing contributes $1.5 trillion to GDP, employs 20 million workers, accounts for more than 70% of industrial R&D, and constitutes the main source of technology for the larger service sector. While knowledge-based services are the largest source of economic growth for the U.S. economy, their long-term performance is highly dependent on synergies with a domestic manufacturing sector. These synergies will be even more important in the future because services are increasingly exposed to foreign competition.

Knowledge-based services can be supplied from anywhere in the world—as long as these foreign sources can rapidly access and assimilate the necessary technology components. This caveat is the critical point for economic growth policy. Considerable research supports the argument that hardware and software components are most efficiently supplied to services by a manufacturing sector that is geographically close and institutionally integrated with the service applications.

Policy debates have raged for decades over the nature and magnitude of underinvestment in manufacturing R&D. The need to resolve the relevant policy issues has increased, as industry is funding less of the long-term, high-risk research that creates the technology platforms supporting new industries and future economic growth.

Unfortunately, only about a third of U.S. manufacturing is high-tech by conventional definitions. Some of the remaining industries develop technologies internally, but most purchase a large proportion of their technology from the high-tech sector. Because a technology acquisition strategy can be more easily imitated by foreign competitors, traditional industries are much more susceptible to exchange rate variations, global economic cycles, and secular shifts in foreign competition. Thus, with global technological capabilities relentlessly increasing, the long-term prospects for the moderate and low R&D-intensive portions of U.S. manufacturing are not good.

This paper presents a conceptual framework and available data as inputs for the analysis of Federal R&D investment strategies. Such strategies must recognize the full range of public and private technology assets constituting a national innovation system. A developed and efficient innovation system has characteristics making imitation by foreign competitors difficult and thereby enables sustained competitive advantage.

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1. Introduction

The attention given by financial markets, policy makers, and the public to investment in information-based services and the underlying infrastructure, particularly the Internet, has accentuated a trend over the past two decades to relegate manufacturing to a secondary role in economic growth strategies. After all, private services account for 64% of gross domestic product (GDP) and government services another 13%.

However, manufacturing is critical to an advanced economy's long-term growth and will continue to be so into the foreseeable future. The United States' manufacturing sector now accounts for only 15% of GDP, but this percentage still translates into a $1.5 trillion contribution to GDP and 17 million jobs.

Especially important is the fact that the service sector acquires most of its technology from manufacturing firms, as indicated in Figure 1 by the much higher share of R&D performed by the manufacturing sector. This fact emphasizes the substantial dependency of services on

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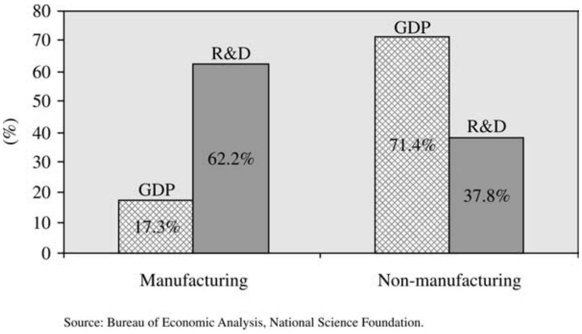


Figure 1. Major industry sector shares of GDP and R&D performance, 2000.

manufacturing firms for technology and thus the critical role of the myriad communications and market transactions between the two sectors.

Recent studies show that the efficiency of such interactions still declines with geographical distance, in spite of the globalization of markets.[1] This phenomenon offers an advantage for large, diversified economies because they have greater potential for achieving synergies from vertical and horizontal integration (real or virtual) among technologies and industries. Moreover, the argument that services are a better long-term economic growth strategy because they are immune to import competition is also suspect. Services are increasingly provided by foreign sources, most recently including developing nations.

Perhaps most important, the so-called New Economy is largely an infrastructure-driven economic transformation. The underlying infrastructure technologies facilitate new economic growth trajectories based on innovations in product, process, and service technologies. However, these three categories of innovation do not automatically happen just because new infrastructure appears. The Internet is greatly increasing the efficiency of intra-company operations, alliances, and marketplace transactions, but the virtual marketplace does not guarantee a flow of new domestically produced products and services.

Economic growth policy therefore needs to be equally concerned with investment in new products and production processes, which can benefit from the IT revolution. After the initial assimilation of IT to increase operation and transaction efficiency, economic gains will be realized more slowly and they will be distributed on a global basis. Economic growth policy must therefore reemphasize technological innovation in hardware and software as major building blocks of future economic growth.

This paper presents a conceptual framework for identifying policy issues affecting economic growth in a technology-based economy with a focus on the manufacturing sector. This framework is then supported by an analysis of trends in R&D—the single most important category of investment for an industrialized nation.

2. A different view of the new economy

Analyses of technology's long-term economic impacts indicate a strong cyclical pattern in which waves of innovation occur. These technology waves have appeared a number of times in the past century. Typically, as the economic boom that follows a burst of innovation proceeds, complacency progressively sets in. The resulting technological obsolescence eventually causes a series of economic crises until a new set of technology trajectories appears. The current IT transformation is a perfect example. Several decades of slow productivity advances with sluggish growth in output resulted in inflation and little or no growth in real incomes. This segment of the long-term growth cycle appeared to come to an end in the late 1990s with huge investments in IT and other technologies (particularly biotechnology).

However, as with past technology waves, the global distribution of the economic rewards is uncertain. Given that all industrialized nations have relatively small high-tech sectors (including the United States), each of these nations is vulnerable to economic decline during the reshuffling that occurs as the new technologies emerge.[2] A major reason is the turbulence that accompanies the initial impacts of the technology. In particular, overestimates of the technology's short-term benefits, the requirements for assimilation, and the new sources of continued innovation all combine to realign competitive positions and put a domestic economy's growth trajectory at risk.

To understand how to sustain and broaden the initial gains in innovation and productivity, four policy questions need to be answered about the future potential of what has been labeled the "New Economy":

1. Is the U.S. economy truly high-tech?
2. Is information technology the only important growth trajectory?
3. Are current R&D investment patterns adequate for sustained growth?
4. What are the sources of R&D investment and how can they be expanded and sustained?

The trends leading to these questions imply broad and sweeping economic change. However, the effects of IT are primarily in the areas of market transaction efficiencies and corporate processes and operations. The major impacts are the creation of some new industries, restructuring of many established industries, and shifts in types of jobs and work location.

Such structural impacts are obviously critically important. These same categories of impacts resulted from the Industrial Revolution in the late 1800s and early 1900s, when major investments in new infrastructure integrated largely isolated regional markets into national ones. New communications technologies greatly increased the flow and timing of information and standardization facilitated the emergence of factories. For the first time, geographically dispersed factories produced components, which were integrated into more complex products at yet another location.

This restructuring of the economic system caused major changes in job content and location. The period was characterized by a distinct lack of pricing power in the key technology-driven markets, which spawned a survival-of-the-fittest corporate environment.[3] The same process is underway today, as technological competence is spreading globally. The significant difference is that the price wars of today's global markets are the result of new national economies whose acquisition and development of technology is eroding market shares of established industrial economies, including the United States. The persistent trade deficit proves this point.

Like the Industrial Revolution, the advent of new product technologies in today's economy is proceeding largely on a separate track from the evolution of the underlying infrastructure. Independent advances in science give rise to new technologies, but do so decades later. The message for policy makers today is that the current economic transformation, like the one a century earlier, cannot be solely infrastructure-based. The new IT infrastructure is pervasive and profound in its potential impact, but it does not guarantee a flow of new innovative products and services.

Realizing benefits from any growth strategy is neither easy nor quick. The "productivity paradox" referred to the fact that investments by U.S. industry in information technology in the 1980s and early 1990s initially had minimal impact on domestic productivity growth. Three reasons for this pattern have become evident:

1. IT investments, while growing rapidly in the 1990s, started from such a small level that only in the late 1990s did the installed base reached a size sufficient to measurably affect national productivity growth.[4]
2. A transition from an R&D strategy focusing on the development and use of stand alone computers to an increasing emphasis on R&D at the systems level, particularly based on linking computers through communication networks, has greatly increased the productivity impacts of IT.[5]
3. Radical technological changes are not easily absorbed and utilized. Major changes in the organization of work, industry structure, and supporting infrastructure have had to occur. These changes took place slowly and thus only by the late 1990s did growth in both productivity and output begin to accelerate at rates not seen for several decades.

Moreover, while much of the economic growth in the past decade has been due to efficiency gains from investments in IT infrastructure, a significant portion has resulted from an increase in private debt to record levels (150% of GDP in 2001). The expected stimulation of inflation from this accumulation of debt has been delayed in part by cyclical effects, one-time productivity increases, and a strong dollar (the latter being due in part to the stock market bubble and the dollar's role as a reserve currency). These conditions are unstable and cannot be expected to maintain their current levels of subdued impact. The policy message is that economic growth strategies need to be reexamined.

> This paper argues that higher growth rates cannot be sustained by just riding the information highway. The evolving IT infrastructure has the capacity to leverage a diverse range of final consumption services, as well as many types of manufactured goods. However, industrial products (hardware and software) are essential components of IT-based infrastructure and IT-based services in general. The implied synergies are real. Therefore, technologically advanced economies are limiting their long-term growth potential if policies allow investment to be channeled into just a few sectors. Diversification not only has the advantage of stabilizing long-term growth, but its synergistic effect raises the rates of growth in all sectors.

A better label for the current economic transformation is the Knowledge Economy. This term encompasses the trends in both IT infrastructure and emerging product and service technologies, which leads policy analysis to the needed broader view of technology-based growth. Clearly, companies in all sectors reflect the transformation to knowledge-based economic activity.[6] However, the locations around the global economy where knowledge is developed and applied to domestic economic advantage are only beginning to be determined.

What is a manufacturing firm?

What constitutes a manufacturing firm is becoming increasingly blurred. Cisco Systems is one of the largest "manufacturing" firms in terms of market capitalization, but it does little manufacturing internally and the majority of its products arrive at the customer without ever having been seen or touched by a Cisco employee (Ansley, 2000). Yet, this company has great influence over the R&D network in the supply chain of which it is a part. Other large high-tech manufacturing firms are no longer classified as such in government databases because a majority of their revenues comes from services. IBM is a prominent example.

For the purposes of this paper, manufacturing is viewed broadly to include hardware and software systems. The main rationale is to distinguish R&D policies for hardware and software and the systems they comprise from services, especially information infrastructure services like the Internet. Within today's technologies, hardware and software are increasingly integrated at both the component and system levels. The resulting systems are then used to provide various services. The new North American Industrial Classification System (NAICS) partially recognizes this reality by distinguishing to a degree between software products and software services.

3. The changing environment for high-tech manufacturing

Many analysts of future economic growth trends argue that the U.S. economy can and will become almost totally reliant on services (implying an equal reliance on imports for manufactured goods). However, the synergies between manufacturing and services are significant and defeat this argument. Much of the output of manufacturing industries is consumed as stand alone products, but increasingly such output is integrated into systems of products that provide services as the final form of consumption (communications, operations management, financial management, wholesale and retail trade, etc.). The integration of hardware and software into service systems requires synergies among multiple levels in the relevant chain of supplier industries. Such supply chain integration still occurs more efficiently within a single economy because of access to specialized labor pools, technical infrastructures, and markets.[7] However, a number of economic factors must be understood and managed to realize these efficiency gains.

The IT-manufacturing interface

First, IT in general and the internet in particular have been touted as the locus of future growth strategies. While massive in its potential impact, the internet does not appear to be more important than previous revolutionary technologies that have also led to widespread changes in patterns of living and working. For example, the mass-produced and hence affordable automobile led to the suburbs, shopping malls, etc. The telephone greatly affected business behavior and location and, combined with the radio, had an enormous effect on information production and distribution (exactly what is being attributed to the internet). While extremely important, none of these technologies were close to sufficient to drive economic growth by themselves. Specifically, each of the above, including the internet, constitute infrastructure. Their economic role is to facilitate private sector investments in a wide range of other technologies, which collectively make sustained economic growth possible.

Moreover, the focus on the internet ignores the immense impact of IT on manufacturing and hence the potential of advanced manufacturing to make major sustained contributions to economic growth. In particular, significant increases in manufacturing productivity are being driven by IT-based integration of internal corporate activity and business interactions among companies in a supply chain. IT also enables substantial increases in the productivity of manufacturing processes. These processes are capital intensive, which implies considerable investment per worker. In fact, manufacturing appears to be spending more intensively on IT than high-tech services.[8]

Such capital-intensive industry structures characterized by massive investment in IT-based technologies offer the potential for substantial increases in labor productivity. Moreover, higher capital-to-labor ratios are resulting in a declining portion of total costs for labor in most areas of advanced manufacturing.[9] Providing labor has the requisite skills to perform the demanding operations in complex manufacturing environments, the resulting high levels of labor productivity result in relatively high pay.[10]

Although these trends are frequently noted, how they happen and why they happen to a greater extent in some economies are not so well understood. Private investment in IT and other technologies is essential, but this investment does not take place in a vacuum. In particular, an elaborate economic infrastructure is required.

In competitive economies, economic infrastructures facilitate (1) the financing of investments in advanced manufacturing technologies, (2) the conduct of advanced manufacturing R&D, (3) the integration of the results of R&D into production systems, and (4) the provision of skilled labor to effectively use both the equipment and associated software. Such infrastructures are difficult to construct and maintain. Economies with efficient R&D networks, venture capital markets, integrated supply chains (virtual or actual), and education and training facilities have competitive advantages that are not easily established—or imitated.

The technology life cycle

Technologies appear, mature, and become obsolete in a series of evolutionary phases, which greatly affect R&D decisions. Thus, a second economic factor is the timing of R&D investments relative to the evolution of an industrial technology. This timing issue has two dimensions: investment decisions directed at attaining market share within a technology's life cycle and those focused on making the transition between life cycles.

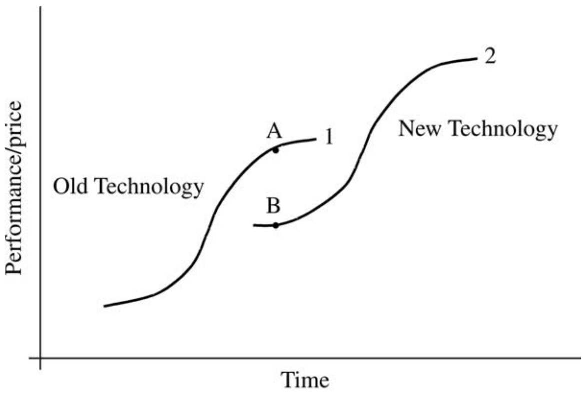
As the market for a product technology expands and this technology is integrated into larger systems, successive improvements in both design and process technologies increase total market value and a subset of firms that have participated in this market come to dominate. Eventually, opportunities to apply the underlying or generic technology decline, design volatility decreases and the product's structure takes on a commodity character (the personal computer is an example). Competition shifts to efficiency in production processes and hence to price and service as increasingly important determinants of market performance.

Over such a life cycle, this evolutionary pattern of technology-based competition increasingly favors less advanced and low-cost economies. They can acquire the maturing product technology and combine it with cheap labor and incremental improvements in process technology. Even within industries viewed as high-tech, this pattern occurs. Certain classes of semiconductors, computers, and many types of software are excellent examples of maturing phases of life cycle patterns and the resulting competitive convergence. Thus, constant but changing R&D investment is required to maintain "first mover" advantage.

In addition, sustained economic growth not only requires constant attention to competitive factors over a life cycle, it demands advance planning for access to the next generation technology. This transition between two generic technology life cycles presents a different set of competitive threats.[11] The greater the differences between two generations of a technology, the greater the risk to individual companies and even entire industries.

Most traumatic is the situation in which a radically new technology appears that performs the marketplace function of the existing or defender technology more efficiently. Such transitions typically demand a different set of research skills for participation in the new technology life cycle, which existing firms do not fully possess. Hence, they assign higher technical and market risk values to the prospective research program, with the result that necessary investments are postponed.

A company evaluating the risk of investing in a new technology faces a projected potential performance pattern, such as curve 2 in Figure 2. Initially, the performance of the new technology (especially relative to cost and hence the price charged) will be below that of the defender technology represented by curve 1.[12] The risk of lower technical or economic performance, possibly



Source: G. Tassey, *The Economics of R&D Policy*, Quorum Books, 1997, Chap. 7.

Figure 2. Transition between two technology life cycles.

for some time, adds to the risk associated with the dynamics of the marketplace. And, these dynamics further compound the innovator's risk because the defender technology seldom gives up without a fight.[13]

Two key policy concerns based on the technology life cycle concept follow. First, within a life cycle, the amount and speed of technological advance achieved by a domestic industry over a technology's economic life is critical, because such gains in performance determine the realized economic return. Innovating industries with high R&D-sales ratios will usually do well, especially over the first part of the life cycle. However, slow adaptation of R&D capabilities over latter portions of the cycle (which can cover extended periods of time) often allow foreign competitors to take significant market share and thereby establish the ability to be innovators in the next generation of the technology.[14]

Second, transitioning between technology life cycles is an even more difficult issue for the policy process to address. A number of high-tech companies manage transitions among successive product life cycles quite effectively. However, the transition between two generic technology life cycles, especially to a radically new generic technology, is seldom achieved by the majority, if any, of firms applying the defender technology. Most of these companies lose out to new industries—either domestic or foreign.[15] This process of "creative destruction" is not a problem, as long as the new industry resides within the domestic economy. Otherwise, value added (jobs and profits) is lost.

In addition to these basic patterns, changes in competitive dynamics are altering the reward/risk ratio for R&D investments within and between technology life cycles. As life cycles compress, R&D at the company level no longer can exist in isolation of a supporting network. To increase R&D efficiency, corporations increasingly require access to R&D conducted by other firms in their supply chains and to the broader technology infrastructure provided by a national innovation system. If domestic R&D resources are not available, U.S. companies do not hesitate to form research partnerships with foreign companies, outsource R&D overseas, or directly invest in foreign research facilities. These research relationships often lead to follow-on foreign manufacturing relationships. Thus, the maintenance of an effective domestic R&D network is essential for attracting domestic and foreign R&D funds and subsequent manufacturing, which increases domestic value added and hence economic growth.[16]

> Major R&D policy issues therefore include the role of government in facilitating efficiency within life cycles and the critical transitions between cycles. In an oversimplified model, applied technology research is automatically initiated by the private sector once an adequate science base is provided and a new technology life cycle is thereby begun. In reality, however, a major concern for R&D policy arises at this transition from basic research to technology research. Here, for the first time, technical risk associated with meeting demand and market risk associated with uncertain demand conditions must be added to estimates of pure technical risk. Combining this additional technical and market risk complicates corporate R&D policy decisions way beyond what is involved in allocating government funds for basic research.

This situation is depicted in Figure 3, which indicates that technology research, with its ultimate objective of market applications, encounters an initial major increase in technical risk, RR′. Such a jump occurs because the scientific principles presented must now be proven capable of conversion into specific technological forms with specific performance attributes that meet specific market needs. The additional risk (RR′) occurring in the early phases of technology research can and does act as a substantial barrier to private investment in R&D.

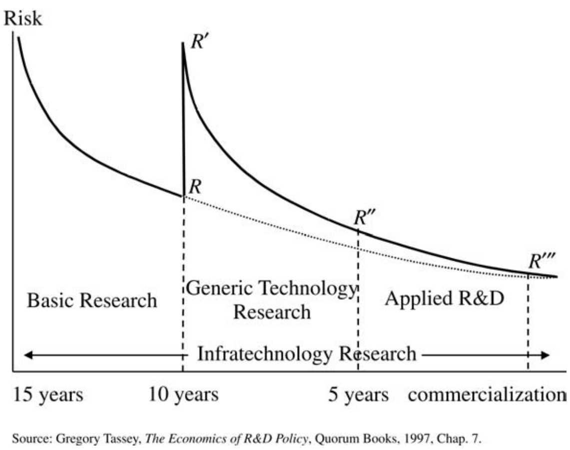


Figure 3. Risk reduction over a technology life cycle.

However, this large discontinuity in the total risk reduction process continues to be debated. If it did not occur, the gradual slope of the curve in Figure 3 would support proponents of no government support for R&D beyond basic science. Understanding the evolution of and the interaction between technical and market risk and the consequent impacts on private-sector investment must be a key element of R&D policy analysis. In fact, the substantial jump in total risk caused by the divergence between market-derived technical requirements on the one hand and research requirements, time discounting, and corporate strategy mismatches on the other can and does lead to substantial underinvestment.

Moreover, consideration of the discontinuity aside, the slope of the risk reduction curve varies depending on a number of R&D efficiency factors. An important one is the availability to domestic firms of a range of infratechnologies, which provide research tools, scientific and engineering data, and the basis for numerous standards that collectively constitute the technical infrastructure of a high-tech industry. Such technical infrastructure has a substantial impact on productivity, but it also has a strong public good character resulting in underinvestment by industry.[17]

In summary, technology life cycles have a number of distinct characteristics that have implications for R&D policy:

- Major scientific breakthroughs, followed by clusters of key technological innovations, set off major long-term economic expansions.
- However, the time between invention, innovation (first commercial use), and major economic impact (widespread market penetration) can be long, spanning several decades. One reason is that the market transition to a new technology life cycle requires contributions by multiple elements of a national innovation system, which typically are not all in place when needed. Thus, this process can take place

in other parts of the world economy before domestic firms using the old technology realize that change has occurred.

- More specifically, such cycle transitions are difficult because firms need complementary economic assets (skilled labor, capital, and technical infrastructure) to successfully develop and market new technologies. These assets may not be available and vary significantly from one life cycle to the next, which makes their acquisition and assimilation difficult.

Supply chain integration

A third major economic factor is the changing structure of U.S. manufacturing industries and the implications for both R&D and technology utilization. Faced with rapid technological change, growing global competition, and accelerating quality improvement expectations, corporations have found managing diverse product and service lines of business increasingly difficult and subject to sub-par performance. Moreover, with external communications and data transfer costs decreasing, much of the rationale for vertical integration has eroded.[18] To concentrate on core competencies, companies are spinning off lines of business. Many of these businesses become separate domestic entities or move to foreign locations.

Each level in a supply chain is therefore now in play in that the combination of more focused corporate strategies and greater foreign competition increases the volatility of shifts in global market shares. Loss of market share in some industries is inevitable and, in fact, not a national concern—if these losses occur in lower value added industries. However, if hollowing out of supply chains occurs in higher valued added industries, the constraints on economic growth are more serious.

One response to the potential for excessive hollowing out is the huge investment in IT-based infrastructure, which seeks to optimize performance for an entire supply chain based on a management system that coordinates the initiation and revision of plans and schedules across institutionally separate supply chain functions. The presumption is that supply chains can be made significantly more efficient through domestic market integration, thereby retaining the higher value added industries within the domestic economy. However, an argument also can be made that such virtual integration supported by a modern IT infrastructure can be easily extended over the entire global economy.

In reality, such integration has turned out to be difficult to accomplish, even domestically. Focusing on a core competence and the implied increased dependency on a larger number of external suppliers and customers is not only requiring new forms of organization for the modern corporation but also supporting infrastructures that leverage modern information/production technologies. The technical infrastructure required to efficiently achieve supply chain integration is as complex as the economic activity it seeks to support.

Companies have tended to try proprietary solutions to integration first, often as extensions of market strategies but just as frequently because an adequate infrastructure for industry-wide integration is not available. The automotive supply chain is a good example. Multiple proprietary systems exist for the transfer of both product design and operations data among firms in the several levels of this supply chain. In spite of industry efforts to standardize on a single infrastructure, little progress has been made. A study of the movement of product design data among levels in the automotive supply chain estimated the costs from inadequate interoperability to be at least $1 billion per year.[19] Because other manufacturing supply chains (such as aerospace) have similar massive product data transfer requirements, the cost to the entire manufacturing sector from the lack of interoperability standards clearly is much larger. Similar problems exist for the transfer of data relating to overall business transactions between companies. One industry group estimated that $82.5 billion was spent on integration tasks of all types in 1998, so the leverage from increased efficiency would seem to be great.[20]

Supply chains differ across sectors, with the impact of integration depending on the competitive structures of the markets involved and the types of relationships among companies, including the availability of key infrastructures. Many of the crosscutting infratechnologies that become the basis for standardized elements of the supply chain infrastructure have a public good character and will therefore receive inadequate private investment. Examples of critical infrastructure include:

- Standards for reliable and secure communication of sensitive information across companies.
- Standardization of interfaces (middleware) among proprietary information systems.
- Standardization of data formats to enable transmission and interpretation among firms.
- Efficient methods for updating standards to accommodate the introduction of new technologies.

In summary, the importance of supply chain integration derives from the trend towards corporate strategies based on core competencies and hence an increased need for greater infrastructure support for efficient marketplace exchanges and effective integration of overall business activity. The public good character of the R&D that produces the infratechnologies serving as the bases for a wide range of interface standards results in substantial underinvestment by industry. Thus, national economies that supply such infrastructure increase domestic efficiency and attract investment at several levels in a supply chain. The economic impact is substantial because multiple levels in a supply chain contribute more to GDP growth than investments leveraging a single industry.

A second major issue with respect to supply chain integration is the effect of vertical disintegration on R&D investment. The trend in corporate specialization is causing a segmentation of private sector R&D. Large, previously integrated companies now expect firms at upstream levels in their supply chain to conduct more R&D.[21] This segmentation is occurring at individual levels in supply chains, as well. Companies are increasingly specializing in one of the major categories of manufacturing activity: product design, component manufacturing, or system integration (assembly).[22] The trend promotes even more focused R&D. The consequence is a significant reduction in private funding of early-phase generic technology research, where the higher risks and longer time horizons require the capture of economies of scale and economies of scope (multiple market applications must be realized to ensure an adequate return on investment).

As partial responses to the underinvestment in generic technology research, users and suppliers license technology from each other and participate in joint R&D ventures, partnerships, and research consortia. Manufacturing firms are also increasingly subcontracting R&D to universities and other firms. Access to external sources of R&D reduces cycle times and improves the overall productivity of company R&D investment.

Many R&D collaborations involve manufacturing and service companies, as well as manufacturing firms from adjacent industries in a supply chain. The frequency of collaborative research is higher within a single economy due to geographic proximity, cultural similarities, and the availability of a single government research infrastructure (national labs, funding, intellectual property rights, etc.) available to all participants.[23] However, such synergies can be difficult to achieve. Coordination, joint management, and assignment of intellectual property rights all inhibit efficient collaborations. More important, the core competency motivation can restrain investment in R&D portfolios that pursue radically new generic technology platforms with broad market potential.

The increasing complexity of manufacturing R&D policy

The final economic factor is simply the difficulty in understanding the several distinct elements of the typical industrial technology, how they are developed, and how they eventually integrate into systems that meet final consumer demand. The development, market transaction, and transfer/assimilation stages all can suffer breakdowns due to complexity of the technology and/or the market and infrastructure systems that attempt to deliver it.

Using biotechnology as an example of technological complexity, Table I lists the multiple areas of science (column 1) that have had to advance before a larger set of generic product and process technologies could evolve. These generic technologies (columns 3 and 4) have been created over the past 25 years and are just now beginning to yield

Table I
Interdependency of public–private technology assets: Biotechnology

		Generic technologies		
Science base	Infratechnologies	Product	Process	Commercial products
• genomics • immunology • microbiology/ virology • molecular and cellular biology • nanoscience • neuroscience • pharmacology • physiology • proteomics	• bioinformatics • biospectroscopy • combinatorial chemistry • DNA chemistry, sequencing, and profiling • electrophoresis • fluorescence • gene expression analysis • magnetic resonance spectrometry • mass spectrometry • nucleic acid diagnostics • protein structure modeling/analysis techniques	• antiangiogenesis • antisense • apoptosis • bioelectronics • biomaterials • biosensors • functional genomics • gene delivery systems • gene testing • gene therapy • gene expression systems • monoclonal antibodies • pharmacogenomics • stem-cell • tissue engineering • recombinant antibody engineering	• cell encapsulation • cell culture • DNA arrays/chips • fermentation • gene transfer • Immunoassays • implantable delivery systems • nucleic acid amplification • recombinant DNA/genetic engineering • separation technologies • transgenic animals	• coagulation inhibitors • DNA probes • inflammation inhibitors • hormone restorations • nanodevices • neuroactive steroids • neuro-transmitter inhibitors • protease inhibitors • vaccines
Public	Public–Private	←——— Private–Public	———→	Private

significant numbers of proprietary market applications (column 5). As described earlier, generic technologies have characteristics of public goods. Industry therefore frequently underinvests in the early phases of a technology's life cycle where proof of concept and laboratory prototypes are essential outcomes with substantial pre-competitive characteristics. Although examples can be found of technological innovations that have occurred before substantial basic and generic technology research have been conducted, the increasing complexity of technology and the competitive imperative to develop it efficiently means that industry generally will not commit the much larger amounts of funds required for proprietary applied research and development until this generic technology base is in place.[24]

Table I also shows the other category of industrial technology with significant public good content—infratechnology (column 2). Infratechnologies are a varied set of technical tools that perform a wide range of characterization, measurement, integration, and other infrastructure functions.

Examples of these functions include:

- Measurement and test methods.
- Artifacts such as standard reference materials that allow these methods to be used efficiently.
- Scientific and engineering databases.
- Process models.
- The technical basis for both physical and functional interfaces between components of systems technologies (such as factory automation and communications systems).

Such technical tools are ubiquitous in the technology-based economic growth process. They affect the efficiency of R&D, production, and marketing. Because individual infratechnologies typically have a focused application and hence impact (e.g. measurement and test methods are applied to specific steps in a production process), their economic importance has been overlooked. However, the complexity of technology-based economic activity and the demands by users of technology for greater accuracy and higher quality have reached levels that require a large number of diverse research-intensive infratechnologies within single industries. The resulting aggregate economic impact of these infrastructure technologies is substantial.[25]

The pervasive and substantial aggregate impact of measurement infratechnologies in high-tech industries is indicated by a study of the semiconductor industry's investment in measurement equipment. This industry invested about $2.5 billion in measurement equipment in 1996, triple the amount spent in 1990. This expenditure was projected to continue growing at least 15% per year.[26] Thus, the cost of not having the required infratechnologies and associated standards in place to support this investment is substantial.

The range and technical sophistication of infratechnologies support a varied and complex standards infrastructure. Infratechnologies are a necessary basis for standardization at all levels in the modern manufacturing process: individual equipment, the process systems level, and the customer/supplier interface. In service industries, infratechnologies help define output, interoperability, security protocols, and intellectual property.[27]

Infratechnologies also include the various techniques, methods, and procedures that are necessary to implement the firm's product and process strategies. Methods such as quality management can be differentiated upon implementation within a firm. However, they must be traceable to a set of generic underlying principles if customers are to accept claims of product quality. Hence, they have an infrastructure or public good character in their development and also in their dissemination, especially for smaller firms.

4. Competitive trends in manufacturing

The above trends imply that an important focus for R&D policy analysis is the supply chains of related industries that make up a technology-based economy. Vertical disintegration (specialization) is distributing R&D across companies and linked industries. The emergence of R&D networks as part of a national innovation system is becoming increasingly evident within the U.S. manufacturing sector. This sector has significantly improved its performance over the past 15 years. Advances in productivity have been accomplished through massive investments in automation and information technology, reorganization of workflow, and restructuring of relationships with vendors and customers. However, the sector faces increasing competition in global markets, as more economies acquire R&D capabilities.

Many economic analyses have been undertaken over this period to explain the relationships between R&D investment, the resulting technology and subsequent innovation and productivity growth, and finally output or GDP growth. While virtually all analysts now agree that technology is the single most important driver of long-term productivity and output growth at the national level, much less agreement exists with respect to how technology affects competitive position and hence growth at the industry level over time. In particular, major strategic issues are in dispute such as the optimal proportions of technology developed within an industry and acquired from external sources. As discussed shortly, U.S. manufacturing industries exhibit a wide dispersion of these proportions.

All manufacturing industries face increased global competition, but only a minority of industries can be said to be capable of competing long-term in global markets. Federal Reserve Board data provide one indicator of this difference in competitiveness. Figure 4 shows the distinctly different growth rates in high-tech and non-high-tech manufacturing.[28] The much higher growth rates of technology-based industries in turn pull investment in further growth.

The high cash flow generated by this growth enables investment in more capacity. Figure 5 shows the same substantial difference in rates of capacity growth, as Figure 4 does for output growth. However, these huge differentials in rates of growth in output and investment in recent years must be qualified by the fact that the manufacturing industries included in the Fed's definition of high-tech accounted for only 8.1% of industrial production in 1998. Moreover, the period of time covered by these data was one of extraordinary investment in IT-related industries, which

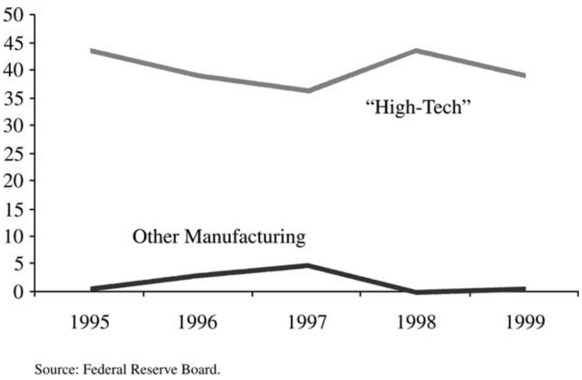


Figure 4. Rates of growth in output for high-tech and other manufacturing industries: Annual percent change, 1995–1999.

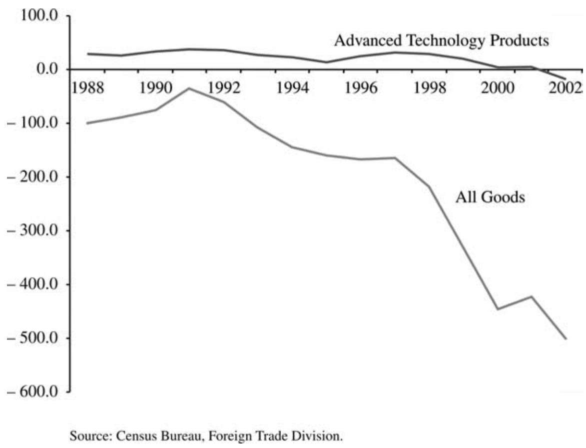


Figure 6. U.S. trade balances for high-tech products and all goods 1988–2002 (in $billions).

accounts for a portion of the performance difference.

However, R&D-intensive manufacturing industries have produced trade surpluses, while the rest of the manufacturing sector has experienced negative trade balances for much longer periods of time. This significant difference in competitiveness is indicated in Figure 6. The Census Bureau's Advanced Technology Products trade balance was positive until recently.[29] From 1988 through 1998, the surplus averaged $28.4 billion, which was a significant percentage of total trade in this class of products. However, this surplus shrunk in the next two years to $5.3 billion in 2000 and turned negative for the first time in 2002. Moreover, these surpluses have been overwhelmed by the huge deficits in trade for all goods, which reached $484 billion in 2002.[30]

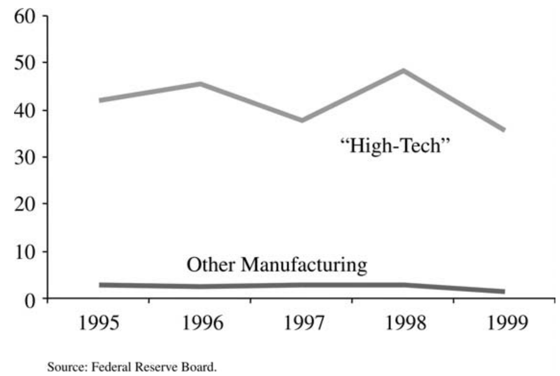


Figure 5. Rates of growth in capacity for high-tech and other manufacturing industries, annual percent change, 1995–1999.

Some of the reasons for the persistent trade deficits are well known by now. Other economies are increasingly able to absorb and improve product technologies. As a technology's life cycle evolves (see Figure 2), product designs standardize and competition shifts to price. The impact of process technology on cost then becomes an increasingly important competitive factor. In recent decades, foreign industries have developed process technologies to the point of being equal or superior to those in U.S. industries. These competitors are now able to produce comparable or even higher quality products at lower cost.

Increased R&D in other nations includes investment in technical infrastructure to support private domestic investment. This evolution of national innovation systems has provided additional incentives to shift U.S. R&D to foreign locations. Whereas traditional direct foreign investment strategies in production and marketing shift lower value added economic portions of supply chains overseas, shifting R&D investment accentuates the trend toward higher value added economic activity abroad.

While low and moderate technology-based domestic industries lose market shares to foreign competitors, technologically advanced industries continue to maintain a trade surplus. Unfortunately, as Figure 6 indicates, this high-tech trade and the resulting surplus that existed until recently are way too small. The relatively small and recently shrinking high-tech trade surplus highlights the need to better understand the relationships among R&D, innovation, and productivity growth over the entire technology life cycle.

5. Productivity growth and R&D policy analysis

Economic research has consistently shown that technological change accounts for the majority of long-term productivity growth. For example, a recent study by Oliner and Sichel (2000) estimates that for the period 1995–1999, the combination of innovation and capital deepening (acquisition of technology through capital investment) has accounted for two-thirds of productivity growth. However, these two sources of productivity growth—technological change and capital deepening—have significantly different roles in determining long-run economic growth.

Both sources are evident in the IT-driven resurgence in productivity during the late 1990s. However, much of the acceleration in IT investment in the 15 years from 1980 to 1995 suffered from the productivity paradox. This term refers to the fact that the expected productivity gains from individual IT investments such as computers, software, and telecommunications equipment did not show up in national productivity statistics. These potential gains were thwarted by the substantial difficulties encountered in integrating individual components into efficient and hence productive systems.

System-level productivity has only recently begun to improve enough to drive aggregate productivity at a faster rate. After increasing 1.5% per year in the period 1991 to 1995, labor productivity (output per hour) increased at an annual rate of 2.7% in the period 1996 to 2000. This acceleration in labor productivity growth elicited glowing commentary on the U.S. economy from many economists and policy analysts.[31]

However, several cautions are in order. First, most economic studies have indicated that the sources of productivity growth are limited to the IT-producing industries and, to varying degrees, the most intensive users of IT. For example, Gordon (2000) concludes that, once changes in statistical adjustments for inflation and business cycle effects are accounted for, all productivity growth is derived from the 12% of the economy involved in the production of durable goods, notably computers. The implication is that the remaining 88% of the nonfarm private business economy has had no significant structural acceleration in productivity growth, including the remainder of manufacturing.[32]

Similarly, a Federal Reserve Board study estimated that the one percentage point increase in the productivity growth rate in the last half of the 1990s resulted about equally from increased investment in IT (computers, software, and communications equipment) and innovation in the actual design and production of computers (including components such as semiconductors).[33] Other studies have concluded that, while the IT manufacturing sector's rapid productivity growth has been a significant contributor to the economy's overall growth rate, IT has added value primarily through capital deepening in the non-IT portion of manufacturing. That is, these studies concluded that IT products, rather than IT producers, are driving productivity increases.[34]

The most important point is that in all these studies the IT portion of the manufacturing sector is the original source of the technology that ultimately drives productivity gains elsewhere. This concentration of the source of productivity growth is due to the fact that the IT sector is where most technological advances have occurred. Moreover, Jorgenson (2001) calculates that the IT-producing industries' contribution is proportionately far greater than IT's 4.26% share of GDP. The effect of technological change is evidenced by pronounced declines in the prices of IT products and services, especially computers.

Many economists project this trend to persist and therefore expect continued decent rates of productivity growth. However, dependency on such a few industries for sustained productivity growth is risky at best. Jorgenson (2001, p. 49), for example, estimates a sharp reduction in TFP if the semiconductor industry's product cycle returns to three years from the more recent two-year pattern. The dependence of future productivity growth on a product life cycle reduction in a single industry that accounts for 0.8% of GDP is truly a "razor's edge" economic growth path. Even if one attributes long-term productivity growth more evenly across all of what is commonly called the "high-tech" sector (IT-related industries plus pharmaceuticals), the U.S. economy's growth is largely dependent on industries that account for only 7–10% of GDP.

Second, virtually the entire debate over the sources of productivity growth has been based on analyzes of trends in labor productivity. However, labor constitutes just one input to economic activity. Consequently, the relationship of labor to overall productivity growth is affected by the magnitude and nature of investments in other inputs. Specifically, the amount of investment in capital and the amount and type of technology embodied in this capital (plus so-called disembodied technological change) are critical determinants of "measured" labor productivity. Thus, a more comprehensive and accurate measure of productivity is needed, which relates output to at least the two major inputs, capital and labor.

Figure 7 shows a 50-year trend in a more comprehensive measure, total factor productivity (TFP), along with trends in average labor productivity (ALP) and real compensation.[35] Real hourly compensation has tracked the comprehensive and hence more accurate measure of productivity, TFP, over the past 25 years. Companies obviously have to pay for all inputs, not just labor, and it is the relationship of output to the weighted average of these inputs that determines true productivity and therefore ultimately profits.

The fact that TFP has grown at a decidedly slower rate than ALP raises questions about the magnitude of the New Economy's impact, especially as the post-1995 resurgence in TFP has not fully reestablished the annual growth rate in the 1948–1973 period.[36] Policy analysis should also

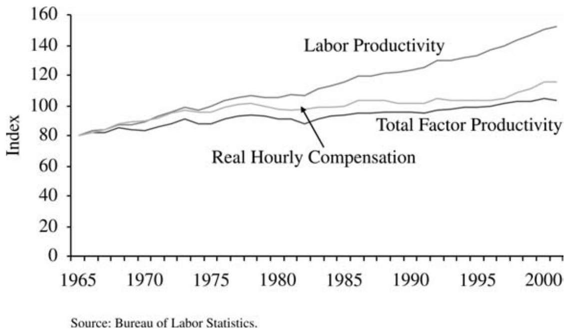


Figure 7. Long-term trends in productivity and income: 1965–2001.

question the sufficiency of an economic growth pattern where virtually all productivity growth is due to a few small industries.

In summary, productivity is an efficiency measure and thereby provides vital information on the relationship between investments and the resulting portfolio of products and services. However, no matter how efficient an economy becomes, at some point this portfolio becomes obsolete and must be replaced with new, innovative products and services. This fact of long-term growth has significant implications for R&D policy. Specifically, an IT infrastructure is providing broad-based efficiency improvements and opportunities to develop many innovative products and services, but these innovations will have to emanate from a much broader R&D investment portfolio than that producing just information technology.

6. Implications of R&D investment trends for policy analysis

The implications of the preceding discussion are that technology is critical for productivity and economic growth, and, because most technology results from R&D spending by the private sector, both the amount and composition of this investment are important policy variables. Policy debates have raged for decades over the nature and magnitude of alleged underinvestment, with no consensus emerging. The importance of this debate has increased, as the national R&D enterprise is changing in significant ways. Four major changes are:

1. The increasing emphasis by companies on short-term payoffs from investments of all types, including R&D.
2. The wider distribution of the sources of R&D across the typical industrial supply chain.
3. A relentless increase in the complexity of industrial R&D, particularly its greater multidisciplinary character and the growing importance of the technology integration phase of R&D.
4. A relative decline in Federal funding of civilian R&D, especially non-health research, which

raises the importance of both the amount and composition of industry R&D funding.

These changes argue for an expansion of R&D policy analysis to include an emphasis on corporate investment strategy within and across technology life cycles and in the context of various positions in supply chains. In particular, a distinction needs to be made between the factors affecting the amount of R&D investment and the composition of this investment.

Amount of R&D

The most frequently discussed technology policy issue is the amount of R&D conducted in the U.S. economy. A commonly used indicator of this policy variable is R&D intensity (R&D-to-sales ratio). This indicator is important because current sales are driven by past R&D and therefore current R&D spending is a predictor of future sales growth. By comparing current R&D to current sales, one gets a rough assessment of the adequacy of new investments in technology for a company's or industry's competitive position in the current and possibly the next technology life cycle.

Figure 8 indicates that most of U.S. manufacturing is not R&D-intensive. In fact, only a few industries have R&D intensity ratios that predict long-term global competitiveness. That is, relatively few industries have the high ratios (in the 8–12% range) that seem to be required for sustained world class innovation. Most important, these industries together account only for 7–10% of GDP.[37]

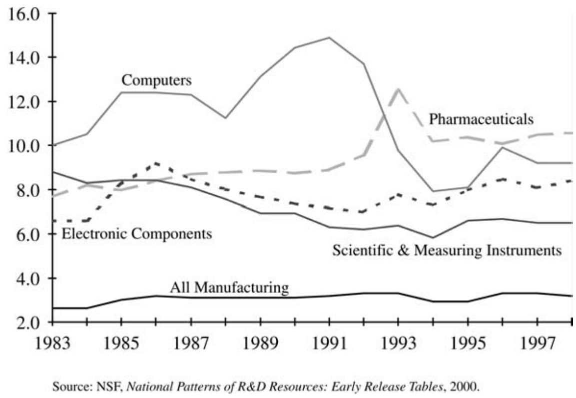


Figure 8. R&D-to-sales trends in manufacturing: 1983–1998 company and other (except federal) R&D funds as percentage of net sales.

The policy implication is that the remaining 90%+ of the economy, including those industries that are moderately R&D intensive, is vulnerable to varying degrees to the increasing R&D intensity from a broad array of industries in other countries. Industries with moderate to low R&D intensities must rely on technology supplied by other industries—domestic or foreign. In a closed economy (no foreign trade), suppliers of technology would obviously be domestic and would not fear cheaper and higher quality imports. However, the increasing ability of foreign industries to acquire or develop modest amounts of technology allows them to compete very effectively with their U.S. counterparts.[38]

Due to downsizing in the face of growing import competition, especially in less technology intensive areas, U.S. manufacturers' sales grew very slowly in the 1980s. The resulting increased proportion of this sector's sales from R&D-intensive industries raised the overall R&D-to-sales ratio for the entire manufacturing sector in the first half of the 1980s from approximately 2.5% to 3.0%, as indicated in Figure 8. However, manufacturing R&D grew more slowly over the next decade and the R&D-to-sales ratio remained flat from 1985–1995. In the 1996–2000 period, both R&D spending and sales accelerated with R&D spending growing slightly faster, resulting in the ratio increasing to 3.3%.

Thus, downsizing and restructuring by many manufacturing firms and even entire industries have resulted in a manufacturing sector that is smaller relative to the overall economy but on average more competitive. However, a 3.3% R&D-to-sales ratio is not adequate to attain long-term competitiveness for manufacturing in a global economy that is rapidly expanding its R&D capability. The wide disparity in R&D intensities among manufacturing industries (Figure 8) implies that not all manufacturing firms or even entire industries have adapted to the demands of global, technology-based competition. Future improvement in real growth rates for this sector will have to come from sustained real growth in R&D sufficient to further increase R&D intensity.[39]

Research has shown that a minimum amount of R&D must be conducted by companies just to maintain the capability to absorb technology effectively from external sources.[40] However, considerably more R&D than this minimum is required for sustained competitiveness in advanced economies. In fact, larger, more advanced economies emphasize the innovation objective of R&D (as opposed to technology absorption objective) as the primary strategy for maintaining high rates of economic growth.[41]

To some degree, decreased R&D investment in one industry can be made up by increased expenditures in other industries in a supply chain, as long as these industries are sufficiently integrated in all phases of economic activity. In particular, research has shown that significant portions of knowledge spillovers from R&D are localized and that technology-intensive industries need to be more clustered geographically than other industries, thereby making attainment of an integrated R&D capability difficult.[42]

These limitations on R&D spillovers are accentuated by the fact that the performance of R&D is, in fact, concentrated geographically. The six states with the highest levels of R&D expenditures—California, Michigan, New York, New Jersey, Massachusetts, and Texas (in decreasing order of magnitude)—account for approximately one-half of the entire national expenditure. The top ten states—adding, in descending order, Pennsylvania, Illinois, Washington, and Maryland—account for nearly two-thirds of the national effort.[43] The implication is that much of the U.S. economy on a geographical basis has weak R&D networks, which means the advantages of regional clustering within supply chains supported by a robust technical infrastructure are not being realized.

The difficulties in achieving acceptable R&D intensities and establishing effective R&D networks are increasing as R&D becomes increasingly dispersed across levels (industries) in the supply chains making up the U.S. economy. The greater complexity of modern R&D and its increased dispersion is creating a need for a more diverse technical infrastructure to support the necessary private R&D investment. To this end, analyzing R&D expenditures at just one level (an industry) in a supply chain will be increasingly inadequate for assessing economic growth potential, as will a singular focus on private or public R&D. Instead, a policy objective must be efficient R&D networks supported by public and private investment to maintain competitive positions in multiple linked industries.

However, the ever advancing complexity of technology and the greater risks associated with long lead times means that almost any distribution of private sector R&D over a supply chain is likely to be inadequate with respect to essential investment in next generation and especially next wave technologies. The latter are the basis for new industries and major international shifts in competitive position. Inadequate investment therefore also reflects a problem with the composition of R&D.

Composition of R&D

As the National Science Board points out, "... any discussion of the nation's R&D must always be careful to distinguish between where the money comes from originally and where the R&D is actually performed".[44] However, the source of funds, as opposed to the performer, controls the composition of the R&D. In this regard, "most of the nation's R&D is paid for by private industry, which provided 65.9% ($149.7 billion) of total R&D funding in 1998. Nearly all of these funds (98%) were used by industry itself in the performance of its own R&D and most (70%) were for the development of products and services rather than for research".[45]

The focus of industry-funded R&D on specific market objectives is accentuated by considerable anecdotal evidence that points to a shift in composition toward short-term development projects. *R&D Magazine* summarized its survey (conducted jointly with Battelle) of industry's projected R&D spending plans for 2000 by stating "Gone ... is industrial support of basic industry R&D, replaced mostly with support of high-tech development".[46]

To some extent, U.S. industry has recognized the implications of this trend and has at least partially compensated for its reduction in internal long-term research by increasing external funding in universities. However, such shifts in location of performance do not change the overwhelming corporate strategic mandate to make R&D pay off in shorter periods of time. Overall, the composition of U.S. private-sector R&D is shifting toward shorter-term objectives, at the expense of next-generation research.

Case studies conducted in the mid-1990s indicate that long-term, high-risk corporate research has been declining for some time.[47] More recent data on trends in U.S. corporate R&D spending are available through surveys by the center for innovation management studies (CIMS) at North Carolina State University in conjunction with the Industrial Research Institute (IRI).[48] The IRI/CIMS surveys provide a unique breakdown of company R&D spending between corporate (central research) and segment (line-of-business R&D) spending. In a sample of 77 firms, an average of 25.8% was funded by central corporate research (acknowledged as longer-term and higher-risk generic technology research) and 67.8% was funded by segments/divisions (shorter-term, commercialization-oriented research).[49] More significant, the IRI/CIMS database provides trend data for a smaller sample of 23 firms.[50] For the 1993–1998 period, the average amount spent on corporate or central research declined from 21.2% to 17.1% of total R&D expenditures. Table II provides similar breakdowns (last column) for some individual companies, which show a lower average allocation to central research of 9.4%.

The decline in funding of long-term, high-risk technology research is not limited to industry. Federal shares of funding for all three major components of R&D tracked by NSF (basic research, applied research, and development) have declined steadily over the past 30 years. During the 1980s, Federal support for applied research was intentionally de-emphasized in favor of increased funding of basic research. Even with somewhat of a renewed willingness to fund generic/pre-competitive applied research in the 1990s, Federal funding in 1998 for applied research was only 70.8% of that for basic research, as reported to NSF by research performers.[51]

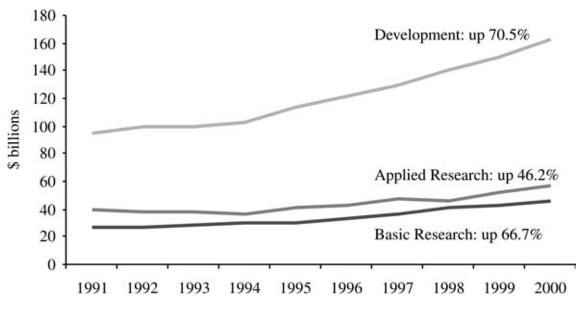
Table II
Fraction of corporate R&D in central research laboratories selected companies, 1998

Company-funded R&D as percent of sales			
Company	Total company	Central lab	Ratio
Nokia	12.2%	1.2%	10.0%
Rockwell	5.0	0.5	10.0
General Electric	3.2	0.4	13.0
Hughes	2.0	0.3	14.0
United Technologies	5.1	0.3	6.5
Raytheon	3.0	0.1	2.8

Source: HRL Laboratories and company data (GE's sales do not include its GECS affiliate).

Figure 9 shows the overall national trends, at least to the extent possible with public data. Applied research, which contains the critical generic/pre-competitive technology research expenditures, has grown the slowest of the three major phases of R&D during the 1990s by a substantial margin. This research represents the transition between scientific research, which has no market objective, and technology development, which is market focused. In the early portion of applied research, market risk enters the calculation for the first time and technical risk takes on new meaning for corporate R&D managers.[52] At this point in the R&D life cycle, time-to-market and technical risk are so high that the investment criteria typically applied to the majority of corporate R&D are not used.

The term generic/pre-competitive applied research exemplifies the huge problem faced by policy analysis due to an inadequate taxonomy for



Source: National Science Foundation, *National Patterns of R&D Resources*, 2000.

Figure 9. Trends in U.S. R&D by major phase of R&D, 1991–2000.

the R&D process. The term applied research is too broad to provide needed insights into funding trends for the truly breakthrough technologies that drive much of economic growth. Companies divide their R&D between a central research facility and their lines of business. Under current NSF definitions, both units will often conduct what is classified as applied research. However, central or corporate research is typically more long-term, more exploratory, and more discontinuous relative to existing corporate market strategies. Hence, such generic or fundamental research is overall much more risky. Companies do not even use the same project selection and evaluation criteria for the two areas of research. The policy significance is large, as investment behavior is quite different in the two cases.[53]

As discussed in the following sections, the Federal role in funding the generic or fundamental phase of technology research (with the exception of biomedical research) has declined in the past two decades. Such research ends with proof of concept, frequently embodied in a conceptual model or laboratory prototype, and typically brings new technologies to the levels of technical and market risk addressable by conventional corporate R&D investment criteria. This milestone is still a long way from the generally agreed endpoint for applied research, which is a commercial prototype.

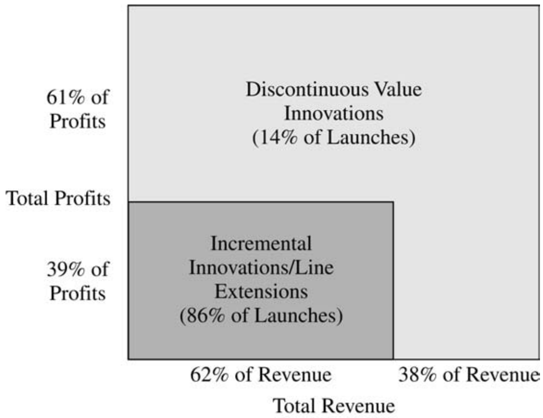
Making a distinction between generic technology research and applied technology research is critical for both corporate strategy and government R&D policy. By the time applied research is initiated, broad technology and market strategies have been determined to a significant extent by earlier exploratory or pioneering research. As described here and earlier, research aimed at new technology platforms is subject to substantial underinvestment by industry.[54]

An important characteristic of generic technology research for policy purposes is its discontinuous character (radically different from the existing corporate R&D portfolio). This characteristic makes the potential market applications highly uncertain for corporate managers. From 11 case studies of radical innovation efforts within major corporations, a team from Rensselaer Polytechnic Institute concluded that "the life cycle of a discontinuous innovation project is profoundly different from a continuous improvement project". The 11 projects studied exhibited several of the categories of market failure described in the next section. In eight of the 11 case studies, the researchers found that government was a major source of funds.[55]

The previous discussion of R&D composition focuses on R&D objectives. Another set of issues with policy implications arises with respect to the R&D process. In particular, the multidisciplinary character of industrial R&D and technology integration are both steadily increasing in importance. Multidisciplinary R&D makes maintenance of minimum threshold levels of science and engineering skills increasingly difficult for individual firms, resulting in increased efforts to partner with private and public institutions or simply not conducting the research.

The systems nature of many emerging technologies has made technology integration a critical part of the R&D process. Studies have shown that differences in the technology integration process are more important than disparities in project management methods, leadership qualities, and organizational structure in explaining variations in R&D productivity. Data indicate that a company's ability to choose technology components wisely and effectively and integrate them has explained variations in time to market and product quality by a factor of two or three over other variables.[56]

The types of compositional R&D market failures identified above significantly reduce the long-term competitive prospects for U.S. industries. In particular, studies have shown that longer-term, more radical (discontinuous) R&D and subsequent innovations have a disproportionately greater impact on economic growth. Based on a survey of high-tech companies in several countries, Figure 10 shows the differential impacts of radical and incremental innovations. Incremental innovations (extensions of existing generic product technologies) accounted for a large majority (86%) of all product launches, but just 62% of sales and only 39% of profits. In contrast, major or discontinuous innovations (radical in the sense they were based on new-to-the-firm generic technologies) were few in number as might be expected (14% of all product launches), but accounted for 38% of sales and 61% of profits.



Source: Kim and Mauborgne (1997).

Figure 10. Profit differentials for major and incremental innovations.

These critical attributes of different types of industrial R&D have been obscured because the traditional policy model treats technology as a homogeneous entity or "black box". Under such a model, basic science is largely a pure public good and therefore funded by government to a significant extent, while the derived technology and its applications (the black boxes) are the province of the private sector with the implication of no role for government.

> This simplistic model is contradicted by the fact that the R&D process eventually producing the black boxes consists of a series of phases creating progressively more applied knowledge. The black box model persists in spite of many case studies of emerging technologies (some discussed below) showing a critical role for government based on characteristics of the earlier phases of technology research that lead to private sector underinvestment. Moreover, the development of black boxes (hardware and software) and their integration into larger technology systems requires an array of infratechnologies, which also have large public good content and therefore suffer from private sector underinvestment.

7. Policy rationales for government R&D support

Trend data have been provided indicating that U.S. industry can underinvest in the type of research that, although long-term and high-risk, ultimately provides the highest rates of return and, in fact, is necessary for long-term economic growth at the national level. Barriers or market failures occur that change the private sector's expected rate-of-return calculations causing systematic underinvestment. Economists have explained underinvestment in R&D largely by the concept of spillovers, which refers to the tendency of knowledge either to directly leak or spillover from the originating source or to be incompletely compensated for in marketplace transactions.

While this phenomenon is an important characteristic of technology-based markets, in reality, such economic activity is much more complicated and suffers from additional barriers not so commonly identified or understood. Specifically, the following six sources of market failure (underinvestment) occur across technologies and at specific points in a technology's life cycle:[57]

1. *Technical complexity:* The multidisciplinary nature of R&D, driven by intrinsic complexity and the systems nature of many emerging technologies is raising risk calculations.
2. *Time:* Increased global competition in R&D is shortening technology life cycles and raising discount rates (particularly for long-term, high-risk technology research).
3. *Capital intensity:* Estimates of risk climb dramatically as the projected cost of a research project increases relative to a firm's total R&D portfolio.
4. *Economies of scope:* Market and hence R&D strategies often are more focused than the potential scope of markets enabled by an emerging technology, thereby reducing investment incentives derived from rate-of-return calculations.
5. *Spillovers:* Leakage or spillover of technical knowledge to companies that did not contribute to a research project is typically greater the earlier in the R&D cycle an investment is undertaken.
6. *Infratechnologies and standards:* Technical tools, methods and techniques, science and engineering data bases, and the technical basis for standards have a public good character and low visibility; such technical infrastructure is

therefore subject to underinvestment over most of the technology life cycle.

Any one of these six barriers can have serious negative impacts on private-sector R&D investment. Moreover, the severity of their impacts can vary over technology life cycles and among levels in supply chains.

More generally, R&D policy must recognize that for long-term, high-risk, technology research, which is discontinuous or radical relative to conventional R&D, industry uses

- Different investment criteria compared to what is used for the majority of industrial R&D investment.
- Different institutional mechanisms for making these investment decisions.
- Different institutional mechanisms for conducting this type of technology research.

8. Federal funding of industrial R&D

Corporate strategists, economists, and policy analysts unanimously agree that technology is the main driver of long-term economic growth. Yet, as pointed out in earlier sections, the high-tech portion of the U.S. and other economies is quite small. The implication is that considerable vulnerability exists as more and more foreign industries attain the capacity to compete in moderate and low R&D-intensive products and services. Because the manufacturing sector conducts over 70% of industrial R&D, it is affected disproportionately by changes in Federal policies toward R&D funding.[58]

R&D funding trends

U.S. R&D spending has increased at an average annual rate of 4.7% in real terms over the past 25 years. However, this growth has succeeded in raising only a small fraction of U.S. industries to the high R&D intensities that seem necessary to sustain competitive positions in expanding technology-based global markets.

Most, but not all, agree that some degree and type of underinvestment in technology research occurs. However, techniques are poorly developed for identifying underinvestment phenomena and then selecting among alternative policy response mechanisms. Moreover, public subsidies for R&D (tax incentives, direct funding, or government laboratory research) have been based on rationales that are often non-economic, leaving the economic growth impacts as an ineffective trickle-down effect.

In spite of these inadequacies, the Federal Government was the main provider of the Nation's R&D funds until the last two decades—accounting for 54% in 1953 and as much as 67% at its peak share in 1964. The Federal share first fell below 50% in 1979 and then stabilized in the 40–45% range in the 1980s. The rapid increase in industry funding of R&D during the 1990s coupled with the general restrictions on Federal spending progressively reduced the Federal share to an all-time low of 29.5% in 1998, as shown in Figure 11.

A frequent observation is that the relative decline in Federal R&D funding is largely due to cutbacks in defense R&D, which is asserted to not directly affect economic growth. This assertion is definitely not true for a portion of DoD R&D expenditures, which over several decades has been largely responsible for the emergence of a number of major new technologies (as described below). Moreover, the non-defense portion of the Federal R&D budget, which arguably is more market focused than the defense portion, has remained relatively constant in real dollar terms for 35 years (Figure 12). A declining defense R&D budget and a static non-defense budget should be closely examined with respect to its adequacy for provid-

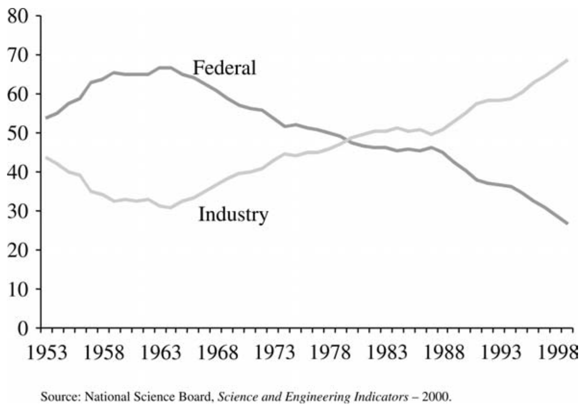


Figure 11. Federal and industry R&D expenditures, 1953–1999 percent of total R&D spending.

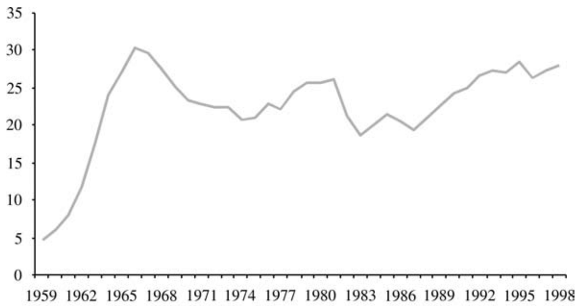


Figure 12. Federal non-defense R&D funds FY1959–1998 (1992 $billions).

ing industry with a range of technology platforms to launch new industries. The models of technology-based economic growth summarized in this paper and the examples of major economic impact from past government R&D funding described in the following sections emphasize the importance of such analysis.

Two critical policy issues should be the point of departure for this analysis: (1) How will the substitution of private for government funding affect the amount of R&D funding over time, and (2) how will this shift affect the composition of R&D?

In the five years from 1994 to 1998, industry funding of R&D grew in real terms by 8.9% per year, allowing many to conclude that no policy issues exist. However, in the previous ten years (1985 to 1994), industry R&D funding grew at an annual real rate of 2.8%.[59] One factor explaining the difference in growth rates in these two periods is the business cycle. Companies fund most of their R&D with internal funds, so R&D tends to go up when cash flow is high and decline when it is low. Given the long-term nature of much R&D and the need to develop new technologies within increasingly short time frames, the amount of R&D funding and its stability over time should be a long-term policy concern.

However, the composition of R&D is probably the more significant dimension of the declining share of Federal R&D funding. Some of the elements of an industrial technology are shared among companies—voluntarily or involuntarily for reasons discussed earlier. The two major shared elements are the technology base of an industry (the generic or fundamental technology) and infratechnologies (techniques, methods, databases, etc., many of which become industry standards). Because these elements are shared, they take on the character of public goods, which imply underinvestment by private sources of funding.

> The more radical and generic the technology, the more difficult it is for companies to (1) hold on to the intellectual property (spillovers occur), (2) diversify into the entire range of new markets created by the technology (economies of scope are not captured), (3) access the required multidisciplinary research capabilities (modern technologies are complex), and (4) rationalize undertaking the required long-term research (high corporate discount rates lower the present value of projected future earnings).

Public-private investment: Generic technology

Criticisms of linear models of innovation (basic science, generic technology, innovations—in that order) are justified. Feedback loops are regular occurrences in which marketplace experiences feed back into product or process design. Moreover, important innovations do occur and then the underlying science is developed to explain how the technology works. For example, Pasteur invented the vaccine and in the process discovered some new principles of microbiology. More recently, packet switching—the basis for computer networks including the internet—evolved to a significant degree ahead of theory.[60]

However, it is hard to imagine apoptosis, antisense, monoclonal antibodies, or other generic biotechnologies being developed through experimentation rather than derived from previous advances in microbiology. In fact, the greatest difference between traditional pharmaceutical research and biotechnology research is that the former was largely trial and error, whereas the latter is based on fundamental science and a set of generic technologies that evolved from this science. The former may prove the existence of a nonlinear model of innovation, but it is far less efficient than the more linear evolution of biotechnology research.[61]

The increasing dependency of innovation on basic science and derived generic technologies is seen in the changing relationship between patents and research. From 1987/88 to 1993/94, the linkage between industrial technology (represented by patents) and science (represented by the citation of scientific papers in patents) tripled and has more than doubled again since then. These studies also reveal that U.S. patents preferentially cite the highest quality research (indicated by research papers with the highest overall citation frequency). Finally, the institutional origins of the papers cited in the patents were dominated by public sector organizations. The analysis showed that 73% of the papers cited in U.S. patents were authored in public sector institutions, such as universities and government laboratories.[62] Thus, for major new technologies, the science base increasingly must be in place before significant and sustained rates of applications can take place. That is, an evolutionary pattern (i.e., a linearity) exists in major technology life cycles.[63]

Part of the difficulty in attaining a consensus model of innovation arises from the increasing dominance of systems technologies. Advances in component technologies within systems create demand for advances in the remaining components to allow the system technology to advance. Moreover, initial advances in some components cross-fertilize advances in other components. These phenomena have given rise to as a "chain link" models of innovation.[64] Such models not only embody interactive relationships among stages in the development and commercialization of technology, but also include complementary roles for several distinctly different technologies. Here, the pattern of technological progress is ascribed more to a mating of complementary technology assets, independent of any evolutionary process.

Unfortunately, such derived demand for advances in component technologies within a broader system technology has been confused with the relationship between the generic technology base underlying each component. For example, a National Research Council paper states that "... development of magnetic core memory for computers did not flow directly from advances in materials research (although it certainly drew upon such research), but from the need to develop a memory system with short enough access times and high enough reliability to support real-time computing".[65] Such a statement reflects confusion between the derived demand for a technology (needs at the system level) and the science and generic technology base (the results of materials research) that enables a specific technology's development (magnetic core memory) in response to that demand.

Equally important for R&D policy is the fact that the advancement of basic science sufficient to allow technology development to begin does not guarantee immediate or even eventual commitment of private sector funds (see Figure 3). Several decades of large-scale funding of molecular biology research by NIH were required before private investment kicked in and spawned a biotechnology industry. A recent analysis of U.S. patent citations in biotechnology found that more than 70% of them were to papers originating solely at public research institutions.[66] And, 20 years after the first biotechnology company went public, NIH still provides research funding to dozens of the more than 300 biotechnology companies. These companies now have "140 products approved and on the market... [and] a pipeline heading for the FDA that could double that number in the next 18 months".[67]

The tremendous growth in health care productivity being made possible by a radically new technology also is creating a new industry with substantial economic growth potential. This phenomenon is occurring in the United States and not in a competing economy because the Federal Government funded both the science base and the subsequent early phases of technology research, allowing U.S. industry and U.S. capital markets to reach positive investment decisions ahead of the rest of the world.[68]

The NIH example is a case study in government response to the entire set of R&D market failures that beset the development of any radically new technology. U.S. R&D policy has condoned government funding of generic technology or more radical infratechnology research when some non-market objective (such as health care) is available as a driver. This philosophy is apparent in the current distribution of Federal R&D funding shown in Figure 13. Health has received continually larger shares of the non-defense R&D budget and the result has been U.S. leadership in biotechnology.

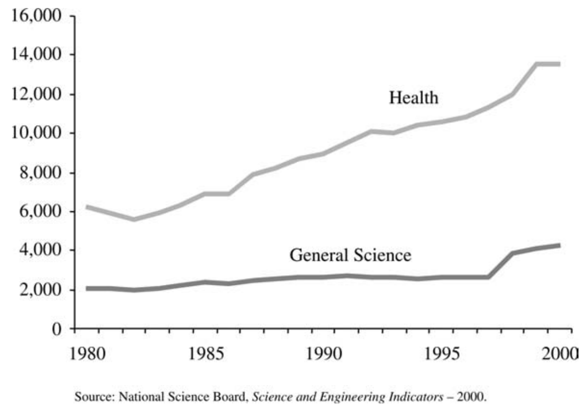


Figure 13. Federal R&D for health and general science, 1980–2000 (1992 $Millions).

In the past, non-market motivations (primarily national defense) allowed Federal funding of major new technologies at threshold levels, which subsequently drove economic growth for decades. The fields of computing and communications provide a number of compelling examples of how government funding played a critical role in advancing generic technologies and achieving minimum thresholds of R&D capability necessary to stimulate takeoff in private sector investment. Federal funding for electrical engineering in areas such as semiconductors and communications technologies (major components of computing technologies) has fluctuated between $800 million and $1 billion since the 1970s. Funding for computer science increased from $10 million in 1960 to approximately $1 billion in 1995. These amounts have represented a major fraction of all research funding in the field of computing.[69]

The majority of this funding went to industry and university researchers. Not only did the government-sponsored research advance key areas of the underlying science and technology, but it also fostered a broad and deep R&D capability that leveraged follow-on private investment by industry. An extremely important aspect of this support is the extension of Federal funding beyond basic scientific research to generic technology and even experimental deployment. For example, before 1970, the Federal government sponsored individual researchers who developed the underlying network technologies, such as queuing theory, packet switching, and routing. During the 1970s, experimental networks, notably the ARPANET, were constructed. These networks were primarily research tools, not service providers. Most were federally funded because, with a few exceptions, the early versions of these technologies were simply proofs of concept.[70] Such preliminary technology platforms were necessary to provide a generic knowledge base to which industry could apply their conventional investment criteria and determine whether to commit funds for applied R&D and eventual commercialization.

During the 1980s, networks were widely deployed, initially to support scientific research. The National Science Foundation (NSF) was the major supporter of networking, primarily through the NSFNET, which evolved into the internet. At this point in networking technology's evolution, industry began to see the enormous economic potential. Companies such as IBM, Digital Equipment Corp., and Compuserve established proprietary networks. These networks were rapidly utilized worldwide for email, file transfers, and electronic funds transfers.

However, as often happens in the evolution of a major new technology, companies with a large share of the initial proprietary applications displayed little interest in the even greater potential of the generic technology. To be broadly successful and thereby have large economic impact, systems technologies such as the internet have to be based on open architectures. This requirement presented a negative investment incentive to firms with substantial commitments to proprietary networks. Moreover, telephone telecommunications companies, whose lines carried the packet-switched information, resisted computer networks, including the internet, because the nature of voice communications networks is strikingly different from the evolving computer networks.[71]

Similarly, IBM pioneered the concept of relational databases but did not pursue commercialization of the technology because of its potential to compete with established IBM products. NSF-sponsored research at UC-Berkeley allowed continued exploration of this concept and brought the technology to the point that it could be commercialized by several start-up companies and then by more established suppliers, including IBM. This pattern was also evident in the development of reduced instruction set computing (RISC). Though the concept was originally developed at

IBM, RISC was not commercialized until DARPA funded additional research at UC-Berkeley and Stanford University as part of its very large scale integrated circuit (VSLI) program in the late 1970s and early 1980s.[72]

Other examples of critical government funding of generic technology research include expert systems, speech recognition, and image processing. Industry began to invest in these and other areas of artificial intelligence (AI) in the 1960s but scaled back when the long time periods required for commercialization became apparent. Continued Federal investments advanced the generic technologies over a decade or more until conventional industry R&D criteria could rationalize investments in applied R&D. Now, private investment is driving the commercialization of many AI technologies.

When defense R&D dominated Federal funding, DARPA determined the Federal portfolio of generic technology research. In the late 1980s, the growing importance of a broad range of technologies for domestic economic growth led Congress to establish a civilian counterpart to DARPA—the Advanced Technology Program (ATP) at the National Institute of Standards and Technology (NIST). ATP's mission is to fund the gaps in private sector funding of generic technology research. Due in part to a lack of consensus over Federal roles in supporting technology research, ATP's funding has been uncertain over the past decade.

Public-private investment: Infratechnology

Infratechnologies are a ubiquitous set of technical tools, which are increasingly important to the productivity of technology-based economic activity. As is the case with generic technology, infratechnology is a quasi-public good, so both industry and government invest in R&D to develop this category of technical infrastructure. As evidenced earlier in the example of biotechnology (Table I), these infratechnologies—either directly or through incorporation in industry standards—are pervasive in terms of their scope and hence their economic impacts. They leverage the productivity of R&D, enhance quality and process control, and facilitate efficient marketplace transactions for complex, technology-based products and services.[73]

Economies of scope are more pronounced in infratechnology research than is the case for much generic technology research. This fact justifies government conduct of a significant portion of infratechnology research, whereas most generic technology research can be co-funded by government and conducted by industry (as in the ATP model). NIST's laboratories provide a wide range of infratechnologies to industry to leverage the productivity of industry's R&D investment. This technology infrastructure ultimately affects all three stages of economic activity: R&D, production, and market development.

Microeconomic studies undertaken over the past decade have documented high social rates of return (SRR) for government investments in infratechnologies in support of manufacturing R&D. A majority of the 25 projects studied yielded SRR estimates that exceed even a high hurdle rate of 25% (by substantial amounts in many cases). Some recent assessments of NIST infratechnology research programs are summarized in Table III. As indicated by the wide range of net present value (NPV) estimates, some infratechnologies are localized in their economic impact, yielding NPVs that are relatively small. However, many such infratechnologies and associated standards are needed by a single industry. Thus, the aggregate NPV from all technical infrastructure supporting a single industry is quite high. Yet, because of their frequent localized effect and the systems nature and general complexity of most technology, individual elements of technical infrastructure are relatively invisible to policymakers.

The outcome metrics selected for these studies are identical with those used by companies in selecting and evaluating the impacts of their R&D portfolios. This allows some degree of comparison between investments in proprietary technologies by industry and investments in the supporting technical infrastructure by government or by industry-government partnerships. However, the primary use is for resource allocation within the two types of investment. One of the many challenges for R&D policy is the identification of technical infrastructure needs followed by a prioritization of those needs and selection of development and delivery mechanisms.

Table III
Economic impacts of federal infratechnology investments: NIST research projects

Industry/project	Output	Outcomes	Measure*
Semiconductors: Software for design automation (Gallaher and Martin, 1999)	• Software model	• Increase R&D efficiency • Increase productivity	SRR: 76% BCR: 23 NPV: $17m
InformationTechnology: Models and standards for computer security (Gallaher *et al.*, 2002)	• Models • Conformance testing	• Increase R&D efficiency • Enable new markets	SRR: 62% BCR: 109 NPV: $292m
Semiconductors and fiberoptics: Laser and fiberoptic power and energy calibration (Marx *et al.*, 2000)	• Calibrations	• Increase productivity • Reduce transaction costs	SRR: 43%–136% BCR: 3–11 NPV: $48m
Chemicals: Standard reference materials (SRMs) for sulfur in fossil fuels (Martin *et al.*, 2000)	• Measurement method • Standard reference materials	• Increase R&D efficiency • Increase productivity • Reduce transaction costs	SRR: 1,056% BCR: 113 NPV: $409m

SRR = social rate of return, BCR = benefit-cost ratio and NPV = net present value. All NPVs stated in 1998 dollars for comparison purposes.

In the case of infratechnology research, gaps have developed between needs and availability to industry. NIST's laboratories provide industry with a wide range of infratechnologies. However, Figure 14 reflects the fact that the budget for NIST infratechnology research has grown at a significantly slower rate over the past 25 years (1977–02), compared with industry-funded R&D. The markedly different growth rates have resulted in the NIST laboratory research budget declining by a factor of two relative to industry R&D spending during this period.[74]

Figure 14. Ratio of NIST laboratory funding to industry-funded R&D: 1977–2002.

9. Funding the gaps: principles of R&D policy

The above examples of Federal R&D funding reinforce the point that the critical policy issues are the amount, timing, and type of government funding for public good elements of technology research. These elements leverage the development of new technologies as a complement to industry's capacity to undertake the required research over a technology's life cycle.

> As long as Federally funded research is viewed as a set of options on further research and the results of each option are reviewed by all stakeholders before deciding to continue, industry's conventional R&D decision making process should kick in at the appropriate point in the R&D process and government's role should diminish rapidly. That is, industry will either reject the projected technology trajectory or take over an increasingly large portion of total research funding. Case studies cited here have shown this pattern to be the case many times over.

As government funding is extended forward in the R&D life cycle, that is, to include applied research and especially development, the market mechanism is increasingly compromised. In contrast, early-phase generic technology research funding serves the role of providing industry with technology platform options and thereby increases the likelihood of a more optimal technology trajectory being selected and/or selected sooner. In essence, this approach implies a portfolio approach to government R&D funding in that the early phases of a number of technology trajectories are funded with the realization that not all elements of the portfolio will eventually become industrial technology platforms.

In addition to advancing the elements of an industrial technology with a public good character, Federal research funds also help create a broader and deeper research capacity in industry and the supporting technical infrastructure. NIH funding virtually created a biotechnology research infrastructure in universities and industry, while being a major technical resource itself. ARPA and NSF funded academic research in all areas of computer network technology. ARPA managers worked closely with the researchers they supported and convened many meetings for information sharing and planning.[75] The resulting broader and deeper R&D establishment permitted more diverse and rapid market applications, once significant private investment kicked in.

> A critical policy lesson is that much of NIH's support of biotechnology and DARPA's support of computer-related technologies and communications networking technology preceded private investment. Additional support then augmented the evolution of the technology base where private investment was too narrow in scope or too resistant to the more radical versions of the underlying technology. The result was world technological leadership, the creation of new industries, and substantial economic growth.[76]

A second policy lesson is that funding for generic technology and infratechnology research is small relative to the subsequent investments by industry in applied R&D, as indicated in Figure 15. At the same time, the public good character of this research creates formidable barriers to private sector investment. Fortunately, the relatively small cost allows government to fund a broad portfolio

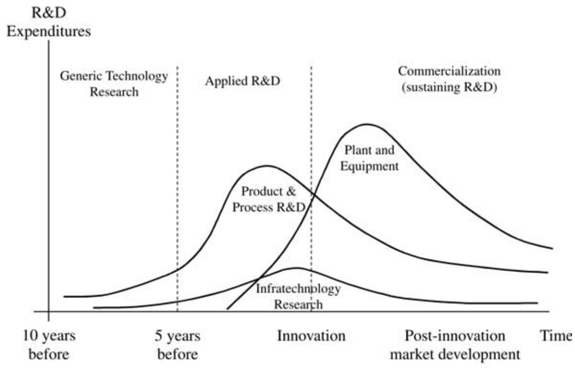


Figure 15. Typical relative expenditures by phase of R&D over technology life cycle.

of research in emerging technologies and infratechnology research. The key requirements for successful government research programs are the targeting of the right technology elements at the appropriate phases in the respective technology life cycles.[77]

Of course, even with ample Federal funding, the complete model of industrial innovation reveals numerous pitfalls along the path to global competitiveness. The United States has become the world leader in biotechnology not only because of sustained Federal research funding but also because of a risk-taking culture supported by an extensive venture capital infrastructure. Yet, over its 25-year history, the biotechnology industry has experienced a number of peaks and valleys of investor enthusiasm. These violent capital market cycles have caused R&D cycles to lengthen and many biotechnology companies to license their technology at unfavorable terms or even sell out to large domestic or foreign pharmaceutical firms at unattractive terms to investors.

An example is monoclonal antibodies (MABs). This technology platform with many potential therapeutic applications was first developed in the mid-1980s and was heralded as the magic bullet for treating cancer and possibly other diseases. However, first generation MABs were not particularly effective for several reasons and investors quickly lost interest. Many companies in this area were acquired or went out of business. However, sustained funding by NIH and a trickle of venture capital allowed research to continue. A decade later, second generation MABs and even newer hybrid technologies that use MABs as targeting devices for other therapeutic agents have appeared. As a result, investor enthusiasm has returned.

Another area of biotechnology with a similar pattern is antisense technology, which blocks the formation within cells of unwanted proteins. In the early 1990s, antisense was a hot technology, but degradation and toxicity problems caused difficulties for the first generation drug candidates. By the mid-1990s, hardly anyone was interested. Now, many of the earlier problems appear to have been solved and the technology is coming back into favor again.

The R&D policy message is that when the time to commercialization is relatively short, perhaps a year or two, risk is relatively easily estimated and incorporated into R&D decision making. For the longer early phases of the R&D cycle, estimated risk increases and inconsistent intra-company and capital market support results. Federal research funding for basic science and the generic technologies based on this science is critical to sustain the innovation patterns that appear frequently in emerging technologies. In addition, the timely availability of infratechnologies is also extremely important. Such technical infrastructure can significantly improve the efficiency of the R&D process and thereby attain critical reductions in R&D cycle times and cost.

> Federal R&D funding alone is obviously not a sufficient long-term economic growth strategy. In fact, this paper has emphasized the critical concept of a national innovation capacity, which includes education and financial infrastructures and the dominance in dollar terms of private R&D funding. However, Federal R&D funding is an essential element of a national innovation system by helping provide a future technology base sufficient to ensure a significant long-term contribution to economic growth by a range of technologies. To this end, a portfolio of emerging technologies should be supported, which includes a sufficiently diversified manufacturing technology platform to capture the synergies of supply chain integration with the rapidly expanding IT-based service sector.

As the Council on Competitiveness recently stated, "Given the rising bar for competitiveness, the U.S. needs to be in the lead or among the leaders in every major field of research to sustain its innovation capabilities".[78]

10. Policy analysis and the development of policy options

Once the need for analysis in a particular area of policy has been determined and specific market failure mechanisms identified and analyzed, policy options must be developed that respond effectively to each type of market barrier. A comprehensive discussion of such a process is beyond the scope of this paper, but its importance for effective R&D policy development should not be overlooked (Tassey, 2003). Unfortunately adequate policy analysis capability does not exist. Neither consensus models of industrial innovation nor appropriate data to modify and utilize such models are available. The two decades of debate over the still temporary research and experimentation (R&E) tax credit, the lack of consensus over the roles of government R&D funding for economic growth purposes, and the continuing inability to agree when each of these two distinctly different policy instruments (tax incentives and direct funding) should be used are clear evidence of the overall problem.[79]

One of the most critical unresolved issues in the R&D policy arena is the nature of interactions between public and private funding of R&D. Economists have researched this question for several decades without resolution. An analysis of why some research shows a positive (complementary) relationship and some finds a negative (substitution) one for this interaction is complex.[80] Findings that government R&D funding either complements or substitutes for private sector R&D spending depend strongly on factors such as the unit of analysis (the firm, the industry or the national economy) or the phase of the R&D cycle funded (basic, generic, applied, or development). Such differences in the estimated impact of public sector R&D should not be surprising, given the inconsistencies among studies with respect to underlying models and data.

This paper has provided analysis targeted at improving R&D policy analysis. To this end, the literature and the case studies cited support the proposition that several critical elements of the typical industrial technology have an infrastructure character, which creates substantial underinvestment by the private sector and therefore demands a public sector response. Other elements of industrial technology—the majority from an R&D spending perspective—require little or no direct government support.

Thus, the characteristics of market failure need to be embodied in a comprehensive model of R&D investment behavior and resulting innovation patterns in order to accurately estimate the optimal amount and composition of R&D and the existing gaps in investment. Only in this context can the various underinvestment phenomena be accurately characterized, which, in turn, will allow appropriate policy responses to be developed. Until the distinctions among the proprietary and public elements of industrial technology are fully understood and used in R&D policy analysis, inadequate policy options will result.

11. Conclusion

A number of changes in the global economic environment have emerged over the past two decades, which demand attention by all industrialized nations. These changes have particularly strong implications for the United States, which once had a virtual monopoly on technology-based economic growth. In particular, the globalization of R&D has greatly magnified the importance for R&D policy of four long-term trends:

1. A skewed distribution of R&D funding in the U.S. economy, with only a fraction of manufacturing and service industries warranting the label of "R&D intensive".
2. A concentration of R&D performance in 10 states, with the remaining states subject to slow growth and persistent job losses.
3. A shift in the composition of industry-funded R&D toward more specific product and process objectives.
4. Skewed Federal funding of long-term, high-risk technology research at the expense of the provision of a diversified portfolio of technology platforms and trajectories as the bases for new industries.

Sustained economic growth in a large and diversified economy such as the United States will require not only more national R&D spending but also the provision of considerably more long-term funding for a range of emerging technologies. In spite of the rapid growth of the service sector, many of these technologies are and will be for the foreseeable future classified in the manufacturing area. Within the U.S. R&D portfolio, substantial Federal funding is currently available for only one emerging technology—biotechnology.

Given the wide range of public and private economic assets that drive long-term growth, a responsive national investment strategy should emphasize those incentives that entice investment in the most productive and immobile determinants of economic growth. Technology generally meets these requirements, even though technical knowledge spills over and thus is relatively easily acquired by users other than the originator.

However, within the technology investment arena, more specific policy targets stand out. One critical objective is R&D capability. States regularly bid against one another to attract production activity, but R&D capability is seldom similarly in play. This is because private R&D assets are closely tied to public research and other infrastructure, whose efficiency requirements may be national in scope. These assets are relatively immobile domestically and even more so internationally, which means that once created they are not easily imitated.

In other words, technology—and the public and private institutions that support its development and use—are interdependent components of a national innovation system. This system is not easily replicated due to the complexity of the actors, institutions, and ultimately market applications that produce the economic benefits. One dimension of this complexity is diversification of an economy's technology base and its myriad applications. The absolute size of a nation's R&D investment is increasingly critical. However, diversification of technology development and utilization across manufacturing and service industries yields three critical additional advantages: more growth opportunities, more stable growth trajectories, and greater synergies among economic sectors. The U.S. economy has made substantial investments in a modern IT-based infrastructure. It must now make the long-term investments in innovative product and service technologies that take advantage of this infrastructure and thereby drive future economic growth.

Acknowledgments

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Notes

1. For example, a recent National Bureau of Economic Research study found that ''technological knowledge is to a substantial degree local, not global, as the benefits from foreign (R&D) spillover are declining with distance''. See Keller (2000).
2. Many different definitions exist for the ''high-tech'' sector of an economy, which is unfortunate for policy analysis purposes. The definition of ''the high-tech sector'' used here includes both manufacturing and service industries grouped into four major categories: high-tech manufacturing (IT-related plus industrial electronics), communication services, software and computer-related services, and pharmaceuticals. See Tassey (1999b, p. 5) for more detail.
3. In fact, both transformations were similar at the broad macroeconomic level, being characterized by productivity gains, strong economy, low-inflation environment, and stable interest rates.
4. Oliner and Sichel (2000).
5. McAfee (2000, p. 11).
6. Blair and Kochan (2000, pp. 1–2) point out that in 1978 the book value of physical assets (property, plant, and equipment) owned by publicly traded non-financial corporations was 83% of a company's capitalization (the value of outstanding bonds and common stock). In 1998, 69% of the average company's value was in the form of intangible (knowledge) assets (so-called ''goodwill''), as opposed to 17% 20 years earlier.
7. The term ''supply chain'' refers to the vertically integrated set of industries that adds value beginning with raw materials and eventually produces a final product or service. Each level (industry) in a supply chain adds value until final demand is met and the sum of the value added by each level is the supply chain's contribution to GDP. An example of a first level in a supply chain would be silicon and other semiconductor materials. These materials are used to manufacture semiconductor devices, which are combined to form electronic components and equipment such as computers. The latter are further combined to form ''systems,'' such as an automated factory that manufactures a product (computer) or a telecommunications network that provides a service.
8. For example, the Conference Board estimates that the manufacturing sector's expenditures on IT are growing at 10–15% per year. Also, the International Data Corporation estimated that the manufacturing sector's spending on web development infrastructure reached $24 billion by 2002, while spending by comparably sized financial services was $17 billion.
9. For example, the amount of equipment required per worker in a liquid crystal display plant is about $1 million. In a software company, the equipment required can be as little as $10,000 per worker (Fingleton, 1999). Higher capital-labor ratios are labor saving, which is particularly attractive in tight labor markets.
10. Manufacturing sector salaries and wages are currently higher than those in the service sector. However, as discussed later in this report, while capital deepening raises measured labor productivity, this ''increase'' is not due to an intrinsic improvement in labor skills. Corporate managers recognize this and do not raise wages and salaries proportionately. Long-term growth in payments to labor depends on increases in skill levels and the consequent contribution to multifactor productivity.
11. A generic or fundamental technology is the basis for specific applications targeted at particular markets. A generic technology could be represented by a conceptual model or a laboratory prototype. Considerable applied R&D is required to create market applications from the generic technology, but without subsequent advances in the generic technology, innovations will be accidental and limited. See Tassey (1997, Chap. 7).
12. This phenomenon can result from several factors: (1) Technical problems that typically occur in newly commercialized technologies; (2) lack of economies of scale due to small initial markets; (3) higher cost due to reliance on a manufacturing process that has not been optimized for the new technology (small initial market shares do not provide sufficient incentive to invest in the necessary process R&D, or, if the innovator is a small company, the initial cash flow may not be adequate to fund that R&D); or, (4) interfaces (standards) between the new technology and other components in the broader technology system are typically not defined early in the technology's life cycle, thereby raising system integration costs.
13. For example, in the face of a challenge from flat-panel displays, manufacturers of cathode-ray tubes continue to reduce costs and improve picture quality, thereby constantly raising the hurdle for the invading technology (curve 1 shifts upward).
14. The video cassette recorder (VCR) is one of the best known examples, but there are many others. A major type of semiconductor manufacturing equipment called a stepper was invented in the United States, but market share is now almost totally Japanese. Oxide ceramics, which every modern commercial wireless communication and detection system incorporates, was discovered in the United States, but Japanese industry today clearly dominates commercial markets. See Tassey (1999b, pp. 29–31) for additional examples.

15. The transitions from vacuum tubes to semiconductors and from cathode-ray tubes to solid-state (flat-panel) displays are two examples.
16. According to NSF data, the two industry groups with the largest absolute shares of R&D funds from foreign sources are chemicals (due largely to pharmaceuticals/biotechnology) and computers—two areas of technology with arguably superior domestic R&D networks. Both groups also have twice as much inflows of R&D funds as outflows to foreign locations.
17. Tassey (1997, Chap. 8).
18. Besanko *et al*. (1996).
19. Brunnermeier and Martin (1999).
20. Enterprise Integration Council (2000).
21. More generally, vertical integration has declined as a framework for corporate strategy for three reasons: (1) Such a structure forges artificial customer relationships reducing price competition, (2) buying components from affiliated divisions of the same company precludes optimization by the customer of multi-component systems, and (3) in a global marketplace of intense competition, corporate managers are having increasing difficulty managing multiple technologies and associated markets.
22. For example, 90% of the firms responding to the Bear Stearns' 3rd Annual Electronics and Supply-Chain Survey (mid 2000) said they planned to increase the use of electronics manufacturing services over the next 12 months.
23. The Industrial Research Institute annual survey indicates that "R&D is becoming more externally collaborative". Industrial Research Institute (2000, pp. 11–13).
24. See Tassey (1997, pp. 63–67) for a discussion of the linearity of the innovation process.
25. For summaries of microeconomic studies of infratechnologies and associated methodologies, see Link and Scott (1998) and Tassey (1997, 1999).
26. Finan (1998). The estimate does not include the labor and overhead required to implement this measurement infrastructure.
27. Tassey (1997, Chap. 9).
28. Federal Reserve Board (http://www.federalreserve.gov/releases/G17/Revisions/19991130/g17.pdf). The Federal Reserve definition of "high-tech" includes computers, communications equipment, and semiconductors.
29. Census' definition of "high-tech" includes about 500 of some 22,000 commodity classification codes used in reporting merchandise trade. Note that this definition is based on "product fields" classified as technology-based, as opposed to "industries" which is used in most other definitions.
30. Data from the International Trade Administration, U.S. Foreign Trade Highlights, Table III. See http://www.ita.doc.gov/td/industry/otea/usfth/aggregate/H99t03.txt
31. Source: Bureau of Labor Statistics.
32. In another paper, Gordon (1999) concludes that the non-computer portion of manufacturing has actually experienced slower productivity growth in the late 1990s compared to the generally acknowledged slow-growth period of 1972–1995.
33. Oliner and Sichel (2000).
34. McAfee (2000, p. 4–5).
35. The main reason ALP is used so frequently is its availability. It is released on a quarterly basis a short time after the end of a quarter, whereas TFP is made available annually approximately 18 months after the fact. Note that TFP is sometimes referred to as multifactor productivity (MFP).
36. During 1995–1999, characterized as the take-off period for the New Economy, ALP accelerated to an average annual growth rate of 2.1%, while TFP grew at less than half that rate (1.0%).
37. Both industry and government definitions of the "high-tech" sector result in a share of GDP within this range.
38. Economic studies have consistently shown a strong relationship between R&D investment and both productivity and output growth (see OECD, 2000; Boskin and Lau, 2000; Oliner and Sichel, 2000, and Cameron, 1998). The work of Griliches (1988) suggests an elasticity of output from R&D of between 0.05 and 0.1 with a social rate of return to R&D of between 20 and 50%. Recent research (Cameron, 1999) has indicated significant variation across industries in the effect of R&D on multifactor productivity growth. However, no evidence has been produced to indicate diminishing returns from increased R&D across the range of R&D intensities found in manufacturing industries. Thus, no support exists for the argument that some industries need less R&D than others. In fact, available data such as that presented in Figures 4, 5, and 6 support the proposition that low and moderate R&D-intensive industries (technology adsorption strategy) do not have a bright future.
39. Based on social rate of return calculations, Jones and Williams (2000, 1998) estimate that "optimal R&D investment is at least four times larger than actual investment".
40. See Cohen and Levinthal (1989).
41. Griffith *et al*. (1998).
42. Keller (2000), Porter (2000), Audretsch and Feldman (1996), Acs *et al*. (1994), Feldman (1994), Jaffe *et al*. (1993), and Rosenberg (1982).
43. Bennof and Payson (2000). California's R&D effort exceeded, by more than a factor of three, the next-highest state, Michigan, with $14.7 billion in R&D expenditures for 1997 (the last year for which data are available). After Michigan, R&D levels for the top ten declined relatively smoothly to $7.4 billion for Maryland. The 20 highest-ranking states in R&D expenditure accounted for about 86% of the U.S. total, while the lowest 20 states accounted for only 4%.
44. National Science Board (2000, p. 2–7).
45. National Science Board (2000, p. 2–9).
46. Studt and Duga (2000).
47. See, for example, Corcoran (1994), Duga (1994), and Geppert (1994).
48. Bean *et al*. (2000).
49. The remaining R&D funds came from the Federal Government (5.2%) and outside contract work (1.1%).
50. However, Bean *et al*. (2000) found this sample to be representative of the entire IRI membership (136 firms), at least with respect to the trend in R&D intensity.
51. National Science Board (2000, pp. 2–31). Note that each phase of national R&D requires more funds than the previous one. For example, in 1998 the United States spent $37.9 billion on basic research, $51.2 billion on applied research, and $138.1 billion on development.
52. See Figure 3 and associated discussion.

53. See Tassey (1997, 1999).
54. Tassey (1999b).
55. Rice *et al.* (1998).
56. Iansiti and West (1997).
57. See Tassey (1997, 1999b) for detailed discussions of these market failure categories.
58. In addition to funding, increasing the amount of R&D conducted is constrained by an inadequate supply of scientists and engineers. The percentage of engineers in the labor force has remained constant over the last 25 years for which data are available (Romer 2000). In 1997, the number of scientists and engineers engaged in R&D constituted 0.8% of the labor force, which is about the same as the previous peak in the late 1960s (National Science Board, Appendix Table 3–25 and Romer, 2000).
59. National Science Board (2000, pp. 2–21).
60. In particular, packet switching for routing messages through the ARPANET advanced empirically beyond theory. See National Research Council (1999, p. 8). Parallel processing is another example of an innovation that did not follow the simple linear model. Demand in the 1980s for increased computing power and the widespread availability of microprocessors led to commercialization, which preceded a good theoretical understanding of how multiple processors can work efficiently together, and spurred advances in that theory. See Office of Technology Assessment (1995, p. 24).
61. By some analysts' estimates, the pharmaceutical industry today develops drugs for 500–600 "drug targets". However, within just a few years the ability of biotechnology to isolate and focus on specific intercellular and intracellular mechanisms will expand the number of drug targets by an order of magnitude to 8,000 to 10,000.
62. Narin *et al.* (1997) and Hicks *et al.* (2000).
63. See Tassey (1997, pp. 63–67, 1999b, p. 21).
64. Klein and Rosenberg (1986).
65. National Research Council (1999, p. 146).
66. McMillan *et al.* (2000).
67. Alan Carr, Chase Hambrecht, and Quist, quoted in "What Next for Biotechs?" *Barron's*, March 20, 2000.
68. Approximately $1 billion of NIH research funding goes directly to industry each year.
69. National Research Council (1999, p. 2).
70. National Research Council (1999, p. 169).
71. For example, voice traffic is handled by a continuous connection (a circuit) for the duration of the transmission, while computers communicate in bursts. Unless a number of these bursts or "calls" can be combined on a single transmission path (seldom the case in complex, high-capacity transmission systems), line and switching capacity is wasted. National Research Council (1999, p. 172).
72. National Research Council (1999, p. 9).
73. Tassey (1997, Chap. 8).
74. As an additional perspective, one corporate R&D establishment, General Electric, employs 9,100 people. NIST—charged with providing technology infrastructure support to the entire U.S. economy—employs 3,200.
75. National Research Council (1999, p. 171).
76. Obviously, private funding increasingly takes over from government funding and becomes dominant as the R&D life cycle progresses. Without such a pattern, little commercial technology would be developed. The appropriate combinations in the right time frames are the key policy variable. For example, Lerner (1996) has shown that SBIR awards are more effective in regions with substantial venture capital availability. However, 40% of these awards have gone to two states (California and Massachusetts), once again emphasizing the skewing of R&D in the U.S. economy in response to a geographically limited innovation infrastructure.
77. California seems to have bought into this policy lesson. In December 2000, the state announced that it has committed $300 million over four years and companies in that state have committed more than twice that amount to develop new generic technologies that will allow replication of the Silicon Valley model (clustering of high-tech firms driven by a new technology, associated infrastructure, and other synergies).
78. Porter and van Opstal (2001).
79. See Tassey (1995, 1996, 1997 (Chap. 6), 1999b) and Whang (1998, 1999) for discussions of tax incentives vs. direct funding as alternative R&D policy mechanisms.
80. See David *et al.* (2000) for a comprehensive assessment of this literature.

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