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R&D Trends in the U.S. Economy: Strategies and Policy Implications

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Executive Summary

"Technology is essential for long-term economic growth". This statement generates little dissent, except occasionally during and shortly after recessions when some associate technology with employment turbulence and job loss. Such myopic views fade quickly as the subsequent economic expansion creates jobs, higher incomes and improved profits.

In spite of this general recognition of science and technology's (S&T) critical role in economic and social well being, debilitating disagreement continues over the mechanisms by which technology drives economic growth and the respective roles of industry and government. S&T policy is a subset of economic growth policy; it therefore needs to be grounded in sound economic rationales, if it is to be appropriately addressed in the broader policy arena.

Key Findings

The dominance of the United States as a source of technology for other economies is declining, with reduced shares in practically every foreign market. Moreover, technology acquired by U.S. domestic companies through imports has more than tripled over the last two decades. This trend is symptomatic of the relentless globalization of R&D capability.

In this context, the most frequently discussed issue is the *amount* of R&D conducted in the U.S. economy. The United States still funds and conducts more R&D than any other country. However, many other economies are rapidly expanding their R&D investment. One indicator is the fact that the other six G–7 nations now invest more collectively in R&D than does the United States. Many newly industrialized nations are ramping up domestic R&D programs, as well.

A commonly used indicator of the amount of R&D undertaken by a high-tech industry is its R&D intensity (R&D-to-sales ratio). In the United States, relatively few industries have the high R&D-to-sales ratios (in the 8–12 percent range) that will allow continued world class innovation. These industries together only account for about 7 percent of GDP.

At the same time, the *composition* of U.S. private-sector R&D is shifting toward shorter-term objectives, at the expense of next-generation research. Annual surveys by the Industrial Research Institute show continued declines in private-sector intentions to fund long-term, high-risk research. Such compositional market failures significantly reduce the competitive prospects for U.S. industries. When global technology-based competition was less severe, the average technology life cycle was sufficiently long to allow U.S. industry to apply lower discount rates to future returns from R&D investment and thereby undertake more next-generation technology research. Neither private-sector nor government research establishments had to be particularly efficient.

These conditions have largely disappeared. Today, central corporate research labs have been de-emphasized, redirected or eliminated entirely. Funding of government research for economic objectives has yet to regain its peak level in real terms reached in the mid-1960s. New programs providing decades of research support similar to those for molecular biology (which created a world-leading biotechnology industry) or for information networks (which led to the Internet) cannot be found — at least not at levels that project first mover advantages for U.S. industries.

U.S. industry is attempting to meet foreign competition by becoming more efficient in conducting applied R&D. This effort currently manifests itself in shorter R&D cycle times. According to one study, industry cut the average R&D project time by 45 percent (18 months to 10 months) in a five-year period (1993-98). However, this study also found that shortening the R&D cycle time was in large part accomplished by reducing R&D project objectives (that is, targeting incremental improvements that can be achieved in less time). Several studies demonstrate that such improvements are not as beneficial to company performance over time as are more radical and risky innovation efforts.

Needed: A Technology-Based Economic Policy Model

The "S" portion of S&T is relatively easy to deal with. Basic science is widely recognized as largely what economists call a "pure public good," which means that massive underinvestment occurs without government support. This premise has been understood and incorporated into policy since the end of World War II.

The "T" portion is another matter. Unlike basic science, technology is a "mixed" good, containing both private and public elements. Because of the complexity of market failure mechanisms and resulting underinvestment patterns, the roles of industry, universities, and especially government are poorly defined, leaving endless debates over different classes of possible policy responses. As evidence of this muddled policy arena, one need only cite a few examples:

- Pronounced shifts in the composition of government R&D funding away from defense to "civilian," without accompanying policy rationales for the redistribution.
- Continued efforts to rewrite S&T/R&D policy in a "post-Vannevar Bush era," with little success.
- Perpetuation of debates over public versus private sector roles based on simplistic taxonomies of the R&D process.

Most S&T analyses gloss over the economics of R&D investment and the associated market failure mechanisms, jumping to a set of poorly defined and supported policy recommendations. For example, support for some form of "collaboration," "cooperation," or "partnering" appears in most policy documents. Yet, few specifics are available regarding what technologies, what point in their life cycles (e.g., what phase of R&D), and what combination of institutions—public and private—should receive support.

This report provides a conceptual basis for describing the economic roles of technology, determining the categories of private investment failures, and identifying the types of economic data needed to conduct analyses for effective policy decisions. A broad range of data are used to apply the framework to current policy issues and to identify the types of data that need to be collected on a regular basis. The focus is on R&D, as opposed to the broader set of S&T policy issues.

The modern R&D investment process is driven by a complex set of technical, economic, and institutional factors. This complexity belies the very simple conceptual models that have influenced R&D policy. As Section 3 of this report shows, a varied set of factors can and do thwart private sector investment in certain types of essential R&D. These sources of market failure derive from the influence of today's emerging technologies and their supporting infrastructures on R&D investment. They include:

- The need for multiple disciplines to be combined within one organizational structure to conduct R&D.
- The effect on risk assessment of the capital intensity of many research processes (i.e., of the cost of these processes).
- A broad and uncertain scope of potential market applications for many of the most important emerging technologies.
- A tendency for excessive "leakages" or "spillovers" of the technical knowledge produced by individual companies to others that did not contribute to the research.
- The unavailability at key points in a technology's life cycle of technical infrastructure (such as standards).
- The emergence of sophisticated users who demand sets of performance attributes that cannot be provided by existing industrial R&D capabilities.

Ultimately, this report argues that the Federal government's role in supporting industrial R&D is poorly understood and therefore inefficiently funded and managed due to the absence of the following three elements of R&D policy analysis:

(1) The R&D policy process needs a conceptual model for assessing government roles in support of technology development, based on the idea of a national innovation system. This includes the concept of networks as the basic structure of a modern, effective R&D establishment. The typical industrial technology consists of a set of distinctly different technology elements requiring the combined efforts of both private and public entities. That is what distinguishes this model from 50 years of simplistic concepts where science is a pure public good and technology is viewed as a homogeneous, purely private good. Because pure public goods are provided by government and pure private goods are provided by industry, government roles in supporting *technology* development have either been undeservedly rejected or poorly conceived and implemented.

(2) Such a model must be grounded in an economic context that provides clear descriptions of the mechanisms by which technology drives productivity and economic growth. Policy studies typically make the general statement that "technology is essential for economic growth" and move on. While this characterization engenders little dissent, it also is woefully inadequate for defining issues relating to technology development and diffusion. In particular, the competitive dynamics of technology-based economic activity needs to be represented in a way that allows incisive analyses of the factors that determine underinvestment at critical stages in a technology's evolution.

(3) More data from a variety of sources need to be collected and analyzed to fully identify, characterize, and assess government roles in supporting industry's R&D investment. Most S&T policy studies not only fail to provide a robust conceptual model and its economic underpinnings, but they offer little or no data either to elucidate the relevant policy issues (in particular, the market failure mechanisms that lead to the need for government support) or to identify and construct policy responses that efficiently remove the market failure.

Major Policy Implications

As the rest of the world becomes technologically competitive, the United States must consider at least three major policy implications:

(1) Acceptable rates of growth cannot be sustained in the future through a small high-tech sector. These industries are under constant competitive pressure. Whereas industries making up U.S. high-tech supply chains previously have been competitive from top to bottom, foreign competition is continuing a process of hollowing out these supply chains, thereby reducing the value added (contribution to GDP) that occurs in the domestic economy. One example is the computer industry, which is simultaneously experiencing a trade surplus in finished computers and trade deficits for all major components. Another example is optoelectronics, which arguably is as important as semiconductors in terms of its "enabling" function for downstream information technology (IT) applications.

(2) To remain competitive, the remainder of the economy will purchase large shares of needed technology from other industries. However, as R&D investment intensity increases around the world, these other industries will increasingly be foreign—unless the domestic high-tech sector is greatly expanded.

(3) Domestic R&D must be treated for what it really comprises—networks of industry, university, and government inputs. These inputs will vary over the typical technology life cycle based on the nature of the particular technology relative to existing R&D capabilities and technology trajectories.

Economists thought at the beginning of the 1990s that the maximum annual real growth rate for the U.S. economy was in the range of 2.0–2.5 percent. An unusual confluence of positive factors raised the actual growth rate to about 3 percent in the 1997-98 period. However, this performance has not allowed the two major components of GDP—profits and real incomes—to grow simultaneously. Corporate profits grew rapidly for most of the

1990s, while real incomes stagnated. In the last two years, real incomes have grown while the growth rate in corporate profits has declined significantly.

Another indicator of overall competitiveness and, therefore, economic growth potential is the merchandise trade balance. This balance has been negative for the past 22 years. Subsets of this broad category of trade are revealing. The more technology-intensive the subset of trade codes (product fields) used to calculate a trade balance, the more favorable the balance. However, the positive balance still realized for trade in advanced technology products also represents only a small fraction of traded merchandise (about 500 of some 22,000 commodity classification codes used in reporting merchandise trade). The limited impact on overall trade and the value added contributed to U.S. GDP reinforces the point that technology-intensive products account for too small a fraction of overall U.S. trade.

This pattern of economic performance is not assessed correctly due in part to misunderstood economic statistics. For instance, labor productivity (which is what gets reported in the media) has grown faster than has total factor productivity (the more accurate measure). Examining total factor productivity trends provides a more accurate and sobering view of actual economic performance and future potential growth, especially in the dominant service sector. Given the major role of technology in productivity growth, the patterns of underinvestment in R&D analyzed in this report should get immediate attention from policy makers.

The sources of economic growth are highly concentrated. Only a few companies or even individual establishments within their industries are going to be successful innovators and users of technology and best practice. A diversified economic infrastructure is necessary to develop enough of these engines of growth to drive national economic prosperity.

Who these successful companies are also will change drastically over time. The 1990s are understood correctly as a period of steady job and business profit expansion. However, these net gains mask considerable churning in various sectors, where many jobs are created and also destroyed. Data from Cognetics, Inc. show that for one yearly change, 1994-1995, almost 700,000 business establishments were added to the economy while slightly less than 600,000 ceased operating. New firms plus expanding ones created 16.2 million jobs, but firms that went out of business and those contracting caused 12.7 million jobs to disappear. All together, 30 percent all jobs in the U.S. economy were in situations of flux—i.e., they were in appearing, disappearing, expanding, or contracting firms.

Even though most net new jobs (84% in the 1992-96 period) come from small firms (<100 employees), growth in employment is highly skewed among these companies. Most small businesses do not create large numbers of jobs. Rather, a small number of fast growing small companies (**"**gazelles**"**) account for the majority of net new jobs. These gazelles are responsible for creating about 70 percent of the net new jobs in the U.S. economy between 1992 and 1996, yet they account for only about 3 percent of roughly 9 million enterprises (corporations, partnerships, proprietorships). This creative destruction represents a healthy U.S. economy, but it also demonstrates the tenuous character of competitive position and hence the need to provide the technical and other infrastructure that enables rapid economic change.

In a Department of Commerce study, rapidly growing companies or individual plants were found to have yielded net employment gains four times the rate of manufacturing plants in general. Such plants were above average users of advanced technology and "best practice" and appear to have benefited from investing in new technology early in that technology's life cycle.

The limited number of highly successful companies and their distribution across the economy combined with evidence that technology is a major factor in their economic success argue for a much broader technology basis for the U.S. economy in order to maximize the number of such companies over time.

> *The end point of this analysis is simply this: The fact that less than 10 percent of the U.S. economy is truly high-tech means that the remaining 90 percent is substantially similar to competing industries in other countries. Although many in this latter group do some R&D and display varying degrees of capability to absorb technology from external sources, they are now basically members of a growing global crowd. Their increasing dependence on foreign supply chains raises the probability that their ability to contribute to future economic growth will diminish over time. Moreover, even the more R&D-intensive industries are experiencing increasing difficulties in rationalizing critical types of technology research that are essential to long-term competitiveness.*

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Gregory Tassey

1.0. Introduction

Over the post-war period, policy makers have slowly realized that technology is critical to growth in the output of goods and services and thereby to growth in economic welfare. Unfortunately, this consensus has not translated into a common view of how technology actually gets developed and utilized. As a result, a seemingly endless debate has ensued over the nature of technology and the implications for private and public sector roles.

If technology is acknowledged as the major driver of long-term growth in an advanced economy, then from the macroeconomic (economy-wide) perspective the *amount* of technology investment is a key factor in determining national growth rates. This issue tends to be the focus of R&D policy debates. However, the *composition* of technology also is critical, especially over more than one technology life cycle. That is, the *types* of technology that an economy either develops or acquires are a significant determinant of long-term growth rates.

In addition, past economic studies have shown that efficiency in the conduct of research and development (R&D) is essential, not only to develop new technologies but also to acquire technical knowledge from external sources of that knowledge. Thus, the *productivity* of the R&D process is increasingly important, not only to take advantage of technology development opportunities but also to acquire technology in an timely and efficient manner. If either of these dual processes—technology development or technology acquisition—fail to function, inadequate flows of technology result and rates of innovation and productivity growth decline.

Current trends in U.S. technology investment create major concerns with respect to both determinants of economic growth: the amount and type of technology produced or acquired. In this regard, economic and technology policy makers have begun to realize that the private sector is underinvesting in certain types of R&D. However, there is little agreement with respect to the types and extent of underinvestment. No one has developed a coherent strategic response.

One contributing factor is that relatively few economists have focused their research on technological change and, of those that have done so, most have failed to target their research toward the needs of policy makers. Moreover, the science and technology (S&T) policy community has largely ignored the economic dimensions of R&D policy.

This report addresses three major problems currently inhibiting effective R&D policy:

(1) A consensus economic model that accurately represents the complex role of technology in economic growth has not been achieved. As a result, data identification and collection are not driven by a coherent set of analytical requirements. Poor policy analysis and protracted debate over basic issues are the result.

(2) Even if such a model were available and accepted, current economic data in general and R&D investment data in particular are highly inadequate for effective R&D policy analysis. Most policy documents refer in passing to only aggregate R&D trends, and then assert market failures and equally vague policy responses. As a result, policy recommendations are poorly constructed and have a weak track record of successful implementation.

(3) To the limited extent that R&D policy analysis is undertaken, it is poorly integrated into the broader economic growth policy framework. The needed synergies among R&D policy, S&T policy, and economic growth policy are simply not in place.

2.0. The Economic Dimensions of Technology Policy

The need for a more analytically-based and data-driven R&D policy derives from four factors:

(1) R&D's multiple roles and growing importance to the U.S. economy.

(2) The private sector's scope and depth of efficiency in developing and commercializing new technologies.

(3) A conflict between individual corporate R&D strategy, bound by time and cost constraints, and the collective need to invest in next-generation technologies to enhance long-term competitiveness.

(4) Sustaining economic performance over the long-term requires an upward shift in total factor productivity (TFP), yet TFP and GDP growth rates have been modest in recent decades.

2.1. Economic Trends

2.1.1. The Macroeconomic Environment. In the 1990s, the U.S. economy performed better than the economies of most other countries. This performance has led many to conclude that technology combined with restructured corporate strategy, organization, and management have permanently restored the United States to the pinnacle of the global competitive ladder.

However, recent economic events are beginning to cast doubt on some of these beliefs or, at a minimum, dampen overly enthusiastic assessments. Specifically, corporate profit growth has been fueled to a significant extent in this decade by downsizing and reorganizations, declining interest rates, corporate buybacks of shares of common stock, lower health care costs, and, in too many cases, manipulation of income statements in the form of repeated "non-recurring" charges.

None of these factors are likely to continue to exert anywhere near their previous levels of influence. Moreover, the two major components of GDP are payments to owners of capital (profits) and payments to owners of labor (wages and salaries). Most of GDP growth in the 1990s has been the result of higher profits. Real incomes hardly budged for most of this decade. In fact, the median household income in constant dollars is unchanged and, moreover, has not grown in real terms since 1980. To increase consumption, consumers have increased household debt as a percent of disposable personal income from 70 percent in 1980 to 94 percent in 1997.

The excessive expansion of credit has been worldwide and has led to equally excessive global consumption. This trend has, in turn, stimulated huge amounts of investment. While investment is in general a good thing, the level of global investment in the 1990s has generated excess production capacity in a wide range of industries. This excess capacity will take some time to eliminate and, while this adjustment is occurring, only the most efficient domestic industries around the world will perform at even acceptable levels.

> *Because technology is the major long-term driver of economic growth, only those industries that have either developed or assimilated superior technology will prosper. Even under generally favorable economic conditions, advanced economies have found sustaining growth in low and moderate technology-based industries to be increasingly difficult. These economies have recognized the growing challenges in technology-based markets arising from competition with each other and increasingly with emerging industrialized nations. However, corporate strategy and government policy changes have not adapted to these challenges, which may undermine the economy's ability to maintain, let alone increase, market shares.*

The following analysis argues that technology development and technology utilization are complementary investments. Unfortunately, the current economic structure of the U.S. economy consists of a small "high-tech" sector that develops new technology, a larger sector that attempts to compete largely by absorbing technology, and the remainder that does little of either. This situation will be increasingly inadequate to sustain desirable rates of growth. In fact, the high-tech sector contributes only a small fraction of GDP. Thus, the U.S. economic system is in need of substantial upgrading not only to take advantage of the tremendous opportunities presented by an array of emerging technologies, but, in the longer term, to even maintain current rates of economic growth as the rest of the world becomes increasingly technologically competent.

2.1.2. Impacts of Technology on Economic Growth. Few argue anymore against the critical importance of technology for the long-term growth of an advanced economy. For most of the post-war period, technological change was confined to a few areas of the manufacturing sector. These short supply chains of industries developed or absorbed technology at a relatively slow pace, with many years typically going by before technical advances in non-market areas such as defense spun-off into mainly producer goods which only indirectly affected consumer products.[1] End users of both products and services had at most only a vague understanding of how technology affected their lives.

Today, the technology economy has become incredibly broad and diverse. The number of producer goods industries that are technology-based is expanding so that, in some cases, entire supply chains are driven by the pace of technological change. Consumers, who were once passive users of technology, now understand and critically evaluate technology to a far greater degree than was the case just a few decades ago. In fact, in many markets consumers have become a driver not just for highly visible products like PCs, but also for many forms of technology-based services ranging from communications to health care. For example, instead of passively waiting for an inefficient trial-and-error development process to occasionally yield new drugs, consumers comb the Internet for information on the exploding number of biotechnology-based pharmaceuticals currently in research and clinical trials and put pressure on companies and government to further accelerate the process. "Chat rooms" exchange knowledge, experience and names of providers relating to a wide range of technology-based products and services.

Consequently, the economic role of technology is getting increasing attention from companies and their governments all over the world. The alteration of old paradigms for what determines competitive success presents enormous opportunity but also immense challenges and risks. The staggering demand for technology across all sectors of the world's economy argues for new and rapid strategic responses. These responses are

[1] The term "supply chain" as used in this report refers to the vertical structure of industries that begin with raw materials and eventually serve a final demand. 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. 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.

evolving in advanced and emerging economies alike. In all cases, some combination of industry and government roles comprise the national economic growth strategy.

2.1.3. R&D Efficiency. As the technological content of domestic production and international trade continues to rise, the importance of a broad, deep, and productive R&D establishment increases. What is referred to in this report as the "high-tech" sector contributed approximately 7 percent of U.S. GDP in 1996.[2] Other industries also conduct varying amounts of R&D, but their R&D intensities (R&D-to-sales ratios) are modest to low. These latter industry groups must import substantial amounts of technology from external sources.

However, technology diffuses from its source industries to many other parts of the economy. Economists estimate that technology, through this diffusion process, accounts for from one-third to one-half of GDP growth and at least two-thirds of productivity growth.[3] Thus, the leverage of the high-tech sector on the rest of an advanced economy is large and therefore extremely important.

When the U.S. economy was unrivaled in its ability to both innovate and utilize new technologies, the time paths of production and diffusion of technology were not particularly important. Today, however, globalization of technology investment and utilization has significantly shortened the average technology life cycle, increasing demands for more efficient R&D and technology assimilation processes. At the same time, the nature of many advanced technologies has become increasingly complex, in terms of depending on multiple science bases as well as being used in higher-level systems technologies. In fact, many industries, including the huge service sector, have had difficulty absorbing and productively utilizing new technologies, as evidenced by sluggish growth in TFP.

> *Thus, long-term productivity growth and the consequent increases in a nation's standard of living depend on both the efficient development and effective use of technology. And, while much technology moves across national borders, economic studies show that a broad and deep domestic R&D capability is required for two critical economic purposes: (1) to develop new technologies ahead of foreign competitors and thereby gain a*

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[2] The high-tech sector is defined here as consisting of four major categories: high-tech manufacturing (IT-related plus industrial electronics), communication services, software and computer-related services, and pharmaceuticals). For alternative definitions of IT-related high-tech industries, see American Electronics Association [1997, p. 128] and Department of Commerce [1998, Appendix p. A1–2]. The AEA definition results in a 6.1 GDP estimate for 1996 and the Commerce definition yields about 8 percent for 1998. To either of these definitions should be added pharmaceuticals, which brings the AEA-defined high-tech sector's GDP contribution to 7 percent. Obviously, no precise definition can be constructed. What is included is a matter of drawing the line at some level of dependency on internally-funded R&D. All of the industries included in the AEA definition plus pharmaceuticals have company-funded R&D intensities of 8 percent or more. The next most R&D intensive industry group is health services with an R&D intensity of about 6 percent. Including this large industry group would add approximately 5.5 percentage points to the high-tech industry GDP contribution. Even with this expanded definition, "high-tech" is still a small fraction of the U.S. economy.

[3] Recent assessments of the literature on this topic can be found in Jarboe [1998] and Jasinowski [1998].

"first mover" advantage, and (2) to effectively absorb and utilize technologies that originate elsewhere.

2.2. Productivity and Technology

Investment in and the effective use of technology are the most important determinants of long-term economic growth. A number of macroeconomic studies over several decades have shown that technical knowledge accounts for one-third to one-half or more of the output of goods and services. These estimates vary because of differences in time periods covered, alternative measures of economic output used, and the scope of the definition of technical knowledge. With respect to the last factor, the degree to which quality improvements contribute to output growth has a significant effect on the estimate of technology's overall contribution to GDP. All of these studies point to the same general conclusion: in the post-war period, technology has been an essential ingredient in the economic growth of industrialized nations.

The U.S. economy has performed well in the 1990s compared to most of the rest of the world. However, the euphoria over this "economic resurgence" needs to be tempered by at least three major trends:

(1) the ultimate measure of economic growth, GDP, has not grown all that impressively;

(2) the major driver of long-term growth—the *rate of increase* in productivity—has been low in recent decades;

(3) the U.S. merchandise trade balance has been negative for the past 22 years.

The trend implied by Table 1 contrasts with the more positive picture of productivity growth, where average labor productivity (ALP) is used instead of the more comprehensive and hence theoretically accurate total factor productivity (TFP).[4] For a good part of the post-war period, these two measures have tracked each other reasonably well. However, as Figure 1 shows, the two have diverged in the 1990s. The reason for this divergence appears to be the result of an underestimate by the Bureau of Labor Statistics of the number of hours worked. This underestimate has the effect of raising estimated ALP relative to TFP.[5] The fact that real income growth tracks TFP supports this explanation. The implication for economic growth policy is that neither enough technology nor its effective absorption by the economy as a whole is taking place.

The controversy over rates of productivity growth has been especially pronounced in the service sector. A NIST-sponsored study of technology investment and utilization in the service sector estimated a rate of return (RoR) on investment in IT capital of 196 percent, compared with an RoR of 11 percent on non-IT capital investment.[6] Such a

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[4] ALP relates output of goods and services to a measure of labor input, while TFP relates output to a weighted combination of capital and labor inputs.

[5] See Roach [1996, 1998a, 1998b].

[6] TASC, Inc. [1998, pp. 52–53] and Link and Scott [1998a, pp. 188–189].

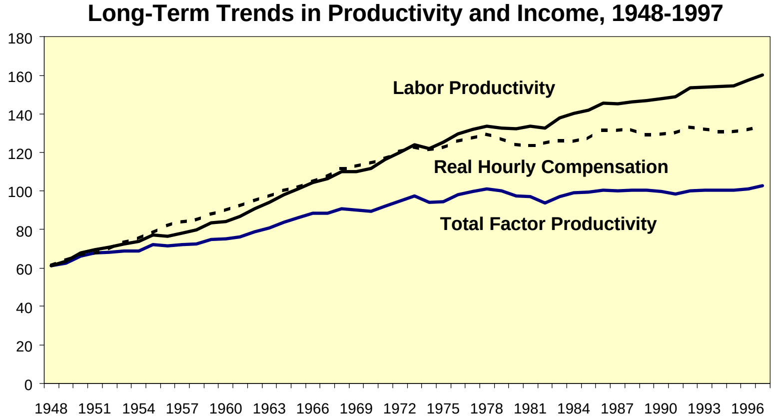
Table 1 ***Total Factor Productivity Growth (TFP) in Post-War Economic Cycles***		
Time Interval	**Ave. Annual Percent Change in TFP**	**Ave. Annual Percent Change in Real GDP**
1948-58 (war to Sputnik)	1.79%	3.8%
1958-73 (Sputnik to oil shock)	2.32	6.0
1973-82 (post-OPEC inflation)	–0.43	2.0
1982-91 (economic restructuring)	0.55	3.5
1991-97 (economic recovery)	0.75	3.0

Source: Bureau of Labor Statistics, Bureau of Economic Analysis

result might seem paradoxical in light of the argument by Stephen Roach and other economists that productivity growth in this sector has been sluggish at best. However, the 196 percent RoR is for capital investment alone. The NIST report points out that "the cost of IT implementation can be four to five times the cost of the investment in hardware and software".[7] Thus, the rate of return on capital investment is leveraged by huge implementation spending. This second investment is going to result in a much lower RoR on *total* investment, which is reflected in the low total factor productivity estimates that Roach points to.[8]

Figure 1

Long-Term Trends in Productivity and Income, 1948-1997



source: Bureau of labor Statistiscs

Table 1 also shows a strong correlation between TFP growth and GDP growth. Even with the addition of the relatively good GDP growth rates achieved in 1997 and 1998, the average growth rate for the 1990s will fall well below that achieved in the early post-war decades. Recent growth rates do not appear sufficient to allow simultaneous advances in *both* corporate profits and also personal incomes—the two components of GDP.

Beneath these national trends are pronounced crosscurrents. Many industries and even entire supply chains are rapidly losing competitive position in global markets, while other industries with significant growth potential are emerging. The current shifts

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[7] TASC, Inc. [1998, p. ES–10].

[8] It is very important to note that this point does not in any way imply that IT is a bad investment. Productivity issues do not deal with the fact that new technologies create new products and services and failure to invest in them will likely mean eventual expulsion from relevant markets. The productivity "problems" are simply an example of the transition costs between major technology life cycles.

in investment to knowledge-based technologies, upheavals in employment patterns, and slow rates of economic growth among industrialized nations are clear manifestations of a long-term cyclical model of economic growth.

> *The last phase of a major technology life cycle is characterized by increasingly intense competition, shrinking profit margins, and structural unemployment and/or, underemployment—all of which have been observed in major industry groups within industrialized nations during the 1990s. Certainly, economic growth policy must help ease transition costs, but it also must facilitate adaptation to the next technology life cycles by identifying the relevant market failures and developing appropriate responses. During a given life cycle, the new technologies that will drive the next life cycle already exist, but with small market shares.[9] Thus, opportunities for adaptation are available, but attempts to take advantage of them usually do not occur until economic conditions have become significantly distressed.*

2.3. R&D Intensity

Because technology is the primary driver of long-term growth in productivity (and ultimately output and real incomes), the economy's investment in new technology should be a critical policy concern. Both the *amount* and *composition* of investment in R&D are key indicators of prospective technological innovation and economic growth.

The U.S. economy has a surprisingly concentrated high-tech sector (as defined by R&D intensity). Technology can obviously be acquired from sources outside an industry, implying that the amount of internal R&D may not be a critical variable. However, economists and business analysts both agree that endogenous R&D is essential, not only to realize first mover advantages from innovative new products, services, and production processes, but also to efficiently assimilate technology from external sources when that is the appropriate strategy.[10]

The most common definition of R&D intensity is the ratio of R&D spending to sales. Because R&D investment is the main source of technological innovation, this indicator is a key predictor of an industry's long-term ability to compete globally. Two alternative R&D investment intensity measures are provided by NSF; one uses company financed R&D, and the other uses total R&D funds available to the industry (company plus federal and other sources). In 1997, the company-funded R&D intensity for the U.S. economy as a whole was 2.9 percent and the total R&D intensity was 3.4 percent. For the manufacturing sector, the corresponding ratios were 3.3 percent and 3.9 percent, respectively.

Several industry groups within U.S. manufacturing maintain high R&D-to-sales ratios, but others invest little or nothing in R&D. In fact, R&D intensity varies from more than 10 percent in high-tech industries to less than 1 percent in others. As

[9] See Freeman [1979].

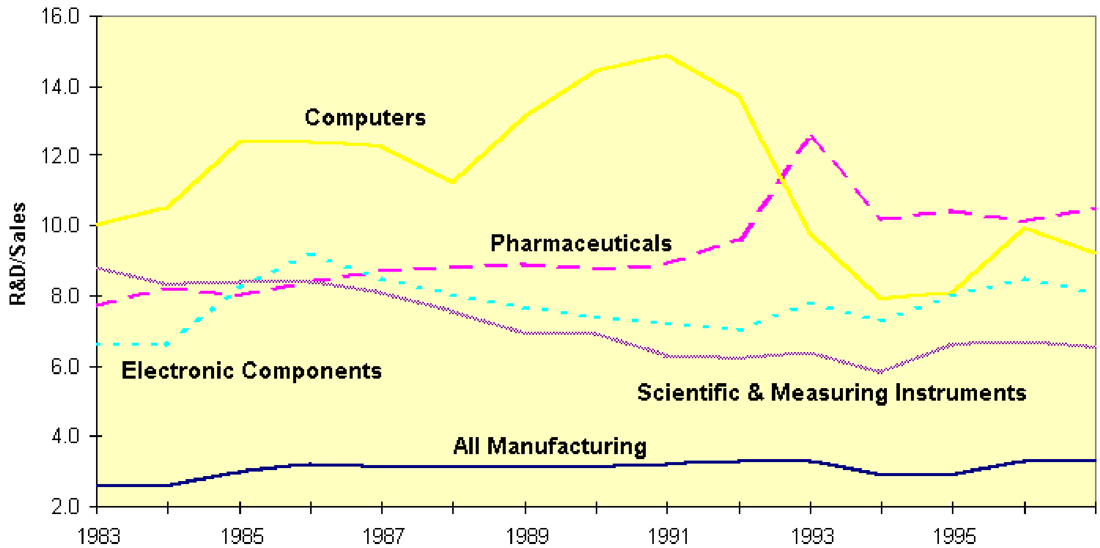
[10] See Cohen and Levinthal [1989].

indicated in Figure 2, the company-funded R&D-to-sales ratio for all manufacturing industries increased from 2.6 percent in the early 1980s to 3.3 percent in 1997.

Figure 2

R&D Intensity Trends in Manufacturing, 1983-1997

Company and Other (except Federal) R&D Performed as Percent of Net Sales



source: National Science Board [1998, Appendix Table 4-25 and updates

Service industries exhibit a similarly wide divergence in R&D intensity. The service sector as a whole had a company-funded R&D-to-sales ratio of 2.2 percent in 1996. However, individual industries vary enormously. Services such as transportation, utilities and FIRE (finance, insurance, and real estate) show ratios of 1.0 percent or less. Health services (at 5.9 percent) and engineering and management services (at 6.1 percent) are in the middle of the pack, while the leaders are 9.4 percent for R&D services and 12.4 percent for computer and data processing services. Surprisingly, service industries that are classified in the same industry group vary substantially with respect to R&D intensity. For example, computer and data processing is classified as one of a number of "business services," but other industries in this group have an average R&D-to-sales ratio of 1.1 percent.

The U.S. economy often is referred to as technology-based, and indigenous R&D capability is essential not only for innovation but also for efficiency in absorbing technology from external sources. High ratios of R&D to sales imply high rates of technological innovation and technology-based competition. High-tech industries also employ considerable technology from other industries and deliver a large portion of the technology used by the rest of the economy. Thus, they are critical to the overall economy along several dimensions.

Even with its significant leverage on the rest of the economy, the high-tech sector is too small to sustain desirable rates of economic growth given the continuing rapid increase in competitive positions of other national economies in moderate technology-based markets. Moreover, the high-tech sector not only is a relatively small portion of the U.S. economy, but also is *concentrated geographically within six states (which account for half the Nation's R&D).*

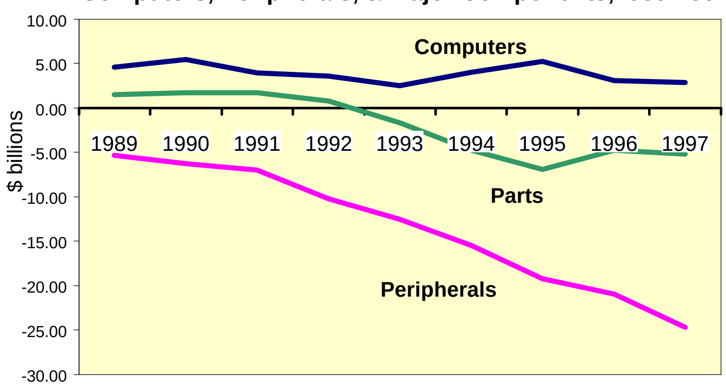
2.4. Competitiveness of Supply Chains

Even the obviously high-tech industries with large R&D investments, such as computers, are not automatic winners in the global marketplace. From an R&D policy perspective, analysis of the factors determining success or failure must carefully define what is meant by an industry.

Computers often are cited as a highly competitive technology-based industry, and the phrase "the computer revolution" is used to convey the notion that computers are driving growth in many other industries as well. While these statements are true in general terms, they are too vague to be a useful guide to policy. In fact, they can be misleading. The term "computer industry" usually is applied to the companies that assemble and sell the actual computer. However, a lengthy supply chain consisting of industries providing silicon, semiconductors made from the silicon and other advanced materials, integrated circuit subsystems composed of an array of semiconductor devices is necessary to produce a computer (which is an assembly of subsystems). For that matter, computers are often sold to become part of larger manufacturing systems and services.

Figure 3

Trade Balances in Computers, Peripherals, & Major Components,1989-1997



source: International Trade Administration

This supply chain contributes far more to GDP than the computer industry alone. A policy focus on the computer industry alone easily can ignore problems in other levels of the supply chain. In fact, Figure 3 shows quite clearly that the major components of the computer are being produced outside the United States economy to an increasing degree. This means that substantial value added by the computer supply chain is occurring elsewhere. The obvious loss of domestic employment and profit generation in a high-tech supply chain should be a cause for concern. Finally, there is no lock on market share at any level in a high-tech supply chain. For example, Taiwanese companies are responsible for both the design and manufacture of over 50 percent of the worldwide supply of notebook computers, regardless of whose label is on the product.[11]

Another supply chain example is optoelectronics, which arguably is now as important an enabling technology as is semiconductors for a myriad of IT applications. The United States did much of the original generic technology research in the 1960s and

[11] McElroy [1998].

1970s. However, Japan, through ever increasing R&D expenditures, now has taken over the optoelectronic component market. In just one area, optical storage technology, Japanese companies now have about $40 billion in annual sales compared with $6 billion for U.S. companies.[12] Yet, farther down the supply chain, U.S. companies are large users of optoelectronic components and are therefore dependent on Japan (and increasingly on other Asian nations, especially Taiwan). Once the competitive position of the domestic supply chain deteriorates, resurrecting it can be extremely difficult.

> *This general problem has become more severe in recent years, as most high-tech supply chains have experienced vertical disintegration. U.S. industries were once characterized by vertically integrated companies with sufficient market power and time to operate integrated R&D programs. Today these companies are dependent on external technological advances by suppliers. This dependency is forcing them not only to help develop their supplier technologies but also to transfer this technology, often to foreign suppliers. The ability of supplier industries to independently conduct the necessary R&D is particularly constrained when those industries are populated by small firms.*

One example is an emerging technology for manufacturing semiconductor components called extreme ultraviolet (EUV) lithography, which is likely to replace current processes for manufacturing integrated circuits. The generic technology was demonstrated at two Department of Energy laboratories (Lawrence Livermore and Sandia). In 1997, DoE licensed the technology to a consortium of U.S. semiconductor manufacturers (EUV Limited Liability Corp.), which is supposed to commercialize the technology. However, the semiconductor equipment manufacturing industry in the U.S. supply chain had deteriorated badly in the 1980s. European and Japanese firms took over market leadership.

Even with considerable assistance from Sematech, this industry has struggled to regain a competitive position. Several U.S. firms (Ultratech Stepper and Silicon Valley Group Lithography) have the potential to compete. However, members of the EUV consortium, such as Intel, want to transfer the new technology to the much larger and better established foreign competitors in order to maximize the potential that the technology will be commercialized. The lesson here is that, once behind, a domestic industry has to run faster than its competition to catch up.

Example of Hollowing Out of a Supply Chain—Light Emitting Diode (LED)

LEDs are one of the oldest and simplest of electronic components. The most common applications are in indicator lamps or alphanumeric displays. Much of the production long ago moved to foreign locations.

Taiwan has been producing LEDs since 1975. Initially, Taiwanese firms only did the final packaging, using chips from Japan. In the mid-1980s, these firms began to produce their own chips, using wafers made in Japan. In the 1990s, the Taiwanese have been producing the wafers as well. This supply chain creep escaped notice, until major R&D efforts by a combination of government and industry in Taiwan succeeded in greatly increasing brightness. High brightness, energy efficiency, and long lifetime for multiple colors are creating huge potential new markets in most standard applications of incandescent and fluorescent lighting. Currently, Taiwan's share of the world market for LEDs has grown to 30 percent, second to Japan's 36 percent. The potential for future growth is much greater.

[12] Bureau of Export Administration [1998, p. II-4].

Sometimes, the loss of competitiveness at one level in a supply chain is rationalized by labeling the technology and its applications at that level as having matured to "commodity" status. That is, the degree of product standardization typical of the latter phases of a technology life cycle reaches the point at which additional profit potential from product differentiation has declined substantially. Profits are now determined more by process technology and simply by overall low-cost production capability. The latter factor tends to favor industries in emerging economies. However, allowing domestic supply chains to be hollowed out for what are often short-term conditions can come back to haunt the domestic economy, as new technology development opportunities and innovation frequently appear as the result of foreign R&D. A number of electronic components, such as LEDs, are providing examples of this life cycle transition effect (see text box).[13]

2.5. Economic Policy is Technology Policy, and Vice Versa

The importance of using the supply chain as the unit of policy analysis cannot be understated. A few R&D-intensive industries cannot support a large, diversified economy. Relying on 7 percent of GDP to drive the remainder of the economy will not work in the long run. The service sector is the dominant user of information technology (IT) but is only just learning how to efficiently develop its unique type of technology. In recent years this sector has averaged $200 billion in annual IT equipment purchases, but they have had to spend around four times that amount to assimilate and use this equipment.[14]

The macroeconomic effects of a narrow technology-based industrial structure is evident in U.S. trade balances. The merchandise trade balance provides an overall indicator of the average competitiveness of manufacturing. It has been negative for two decades and recently is becoming more so (the merchandise trade deficit reached a record $219 billion in 1997 and was even larger in 1998).

Economic studies show that export opportunities for advanced economies such as the United States depend on the use of increasingly sophisticated technology. This fact is reflected in subsets of merchandise trade that are technology-based. A group of industries designated by the Department of Commerce as high-tech include significant numbers of high-tech products but also include less technology-intensive products (called the DoC–3 industry basis for technology-based trade). This industry group maintained a positive trade balance until 1994 but has been negative since that time. A more narrow definition of high-tech trade that only includes selected advanced technology trade codes across industries still yields a positive trade balance.

[13] Asian Technology Information Program [1998].

[14] Lenzner and Gordon [1999] provide an example: "Companies have spent billions in recent years on "enterprise software" from SAP, Oracle, PeopleSoft and the like. And for every dollar clients have put up, Andersen bills another $4 to $10 for customizing it, installing it, lashing it to other systems and training people to use it. If software were simple, Andersen would be out of work."

In other words, the more technology-intensive the subset of trade codes (or product fields) used to calculate a trade balance, the more favorable the balance. However, the positive balance realized for trade in advanced technology products also represents only a small fraction of traded merchandise (about 500 of some 22,000 commodity classification codes used in reporting merchandise trade). The limited impact and hence the value added contributed to U.S. GDP reinforces the point that technology-intensive products comprise too small a fraction of overall U.S. trade.

Entire supply chains obviously can contribute more to GDP than one or two levels in these chains. The decline in the less technology-intensive trade balance (DoC–3) implies a hollowing out of actual and potential value added from so-called high-tech industry groups. The only viable long-term policy response is to broaden the economy's technology base.

The conventional wisdom seems to be that mature industrialized nations are constrained to grow more slowly (2 percent to 3 percent per year) than newly industrialized nations (7 percent to 10 percent). Some economists have pointed to a convergence of economic growth rates over time, at least within major technology cycles. They argue that nations progress technologically not only through domestic innovation but also through technology they acquire from the perhaps 10 to 20 nations that are the technological leaders. Because the laggards have a good deal more to learn from the leaders than the reverse, the balance of trade in ideas inherently favors the laggards. This relationship appears to have led to convergence in national technology capability in the 19th and 20th centuries, during an era of rapid technological advancement.[15]

However, no economic theory proves that the growth rates of advanced economies inevitably have to slow down to only 2–3 percent per year. The reasons for current slow rates of growth are linked to past amounts and types of investment. These investment patterns can be analyzed and changed through an effective economic growth policy, with R&D policy as one element.

> *One commonly expressed belief is that globalization has increased convergence to the point that sustainable competitivee advantage is no longer possible. This is definitely not the case. Certain economic assets, including technology-based ones, are less mobile than others. This means that, once acquired, these assets are not easily exported or imitated.[16] Each nation has a unique combination of public and private economic assets. Beyond political, cultural, and general business practices and organizational modes, competitive positions in today's technology-based markets are determined by a complex set of factors. These include synergies from supply chain effects, increasing returns from network externalities,*

[15] Baumol [1986].

[16] Doremus et al [1998] point to enormous differences among multinational companies, which they trace to the unique political and economic characteristics of their home countries. See also Kogut [1998].

installed-base and lock-in effects, extramural R&D strategies, and the availability of supporting technical infrastructures.[17]

As the following sections will argue, supporting such a complex national innovation system is a daunting policy objective. Developing effective technology-based growth policies is achievable only with a combination of the right conceptual framework and the appropriate technical and economic data.

Unfortunately, in the face of wrenching change, U.S. economic growth policy has struggled for several decades to make a convincing case for a greater national investment in research and development and, even more so, for an appropriate role for government in support of this investment. This effort has been extremely weak for several reasons:

(1) The R&D policy community has failed to adequately articulate the economic case for technology and the process (R&D) that produces it.

(2) What passes for policy analysis has failed on several counts, including trend identification and market failure analysis.

(3) Matching appropriate policy responses with specific market failures is hardly attempted. The vast majority of policy reports simply assert the importance of technology, skip the market failure analysis, and therefore fail to match market failures with appropriate policy responses.

Congressman George Brown (D–CA) summed up the problem for R&D policy particularly well:

> *"[We have] a clumsy and unsophisticated set of tools for evaluating the best of human innovation and thinking. We also need to be conducting outcomes assessments for our science and engineering activities and we need to collect the data needed to make these assessments"*

3.0. Technology Development and Life Cycle Models

As increasing numbers and types of technology permeate the global economy and as the number of technology-based competitors grows, the volatility of global markets will increase. Technology (and hence R&D) life cycles will continue to shorten, industry structures will evolve more rapidly, and employment opportunities will be more volatile. To deal effectively with this complexity, decision makers need a realistic and policy-relevant economic framework of investment and performance over the technology life cycle and, equally important, the transition between life cycles.

A technology-oriented economic growth policy is needed because private markets do not function completely efficiently by themselves. Technology-based industries experience varied and often severe market failures, especially at certain points in their life cycles. Some aspects of R&D-related market failures are easily understood, such as

[17] Tassey [1992, Chap. 12; 1997, pp. 225-226].

the fact that science is largely a pure public good and receives little private financing. Research in basic science requires very long time horizons, the results are highly unpredictable, and the knowledge produced diffuses rapidly and is almost impossible to fully own. Basic research clearly requires government funding.

From an investment incentive perspective, technology research is much more complex and hence difficult to understand. For most of the post-war period, the process of technology-based growth has been grossly oversimplified, resulting in policy gridlock. To remedy this problem, efficient and effective R&D policy in support of broader economic growth objectives must derive from an accurate conceptual model of how technology evolves over a series of life cycles.

3.1. The Technology Life Cycle

Peter Drucker in his classic 1985 *Harvard Business Review* article simply but accurately summed up the nature of technology-based progress:

> *"Knowledge-based innovations differ from all others in the time they take, in their casualty rates, and in their predictability, as well as in the challenges they pose to entrepreneurs…They have, for instance, the longest lead times of all innovations. There is a protracted span between the emergence of new knowledge and its distillation into usable technology. Then there is another long period before this new technology appears in the marketplace in products, processes, or services…To become effective, innovation of this sort demands not one kind of knowledge but many".*

Drucker argues that major technology life cycles have persistently taken about 50 years from the initiation of significant basic research to the emergence of market applications. Simple numbers—the increasing resources around the world devoted to scientific and technology research—argue for a reduction in this time frame in the future.

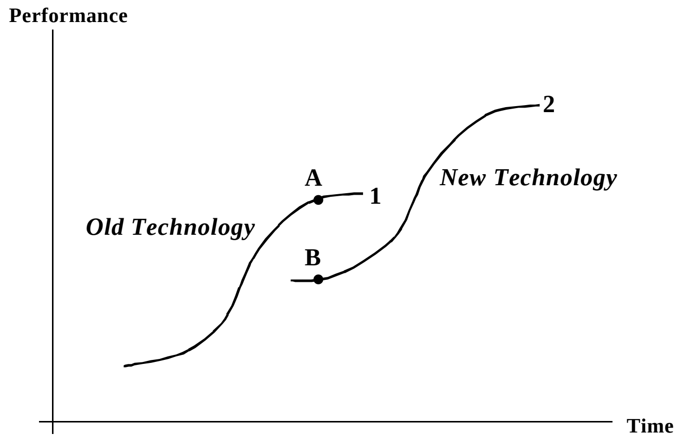
Within these long-term cycles, national economies will undoubtedly vary in how they absorb scientific advances and demonstrate economic potential through technological proof of concept. This fact raises a critical issue from a national economic growth perspective: How can the domestic industry gain early access to both the basic science and the generic technology based on that science?

The technology assessment literature identifies three distinct cycles. The shortest and least controversial is the "product life cycle," which is simply the time from concept or initiation of product development through market penetration and eventual decline. A number of product life cycles are typically derived from the same underlying generic or fundamental technology, which collectively forms a "generic technology life cycle". The generic technology is not static but evolves during such a life cycle. However, this evolution is not major compared with differences from the previous generic technology that drove product development for the same market functions before being replaced by the current technology. Finally, several generations of generic technology life cycles typically evolve from the same underlying set of basic scientific principles. Eventually, a major new science base appears, allowing a transition to a new long-term "major technology life cycle" or "wave".[18]

Over the typical generic technology life cycle, product technologies become progressively more stable. As opportunities to apply the underlying or generic technology decline, design volatility decreases and an industry's product structure takes on a "commodity" character (electric power transmission 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 now maturing technology and combine it with cheap labor and incremental improvements in process technology. Even within industries viewed as high-tech, this pattern occurs. For example, certain classes of semiconductors, computers, and many types of software are excellent examples of maturing phases of this life cycle pattern and the resulting competitive convergence.

Figure 4

Transition Between Two Technology Life Cycles



The transition between two generic technology life cycles presents a different set of competitive threats. The more radical the transition between two cycles, the greater the risk to individual companies and even entire industries. Such a transition typically demands multidisciplinary skills needed to conduct the research for the new technology life cycle, skills that existing firms do not fully possess. Hence, they assign higher technical and market risk values to the prospective research program. A company considering undertaking the risk of investing in the new technology faces a performance curve, such as curve 2 in Figure 4, that initially will be below the existing or "defender" technology (represented by curve 1). The risk of low performance technically, possibly for some time, adds to the market risk associated with the dynamics of the marketplace.

Therefore, two key policy issues based on this technology life cycle concept are

(1) *Within* a technology life cycle the amount and speed of advance achieved by domestic industry over a technology's economic life is critical because these

[18] Schumpeter [1939, 1950] and Caracostas and Muldur [1995, p. 77]. Several generations of microprocessors are an example of product life cycles "nested" under a "generic technology life cycle" (integrated circuits). These generic technology cycles are, in turn, nested under a major technology life cycle (solid-state digital electronics). See Tassey [1997, Chap. 4].

performance variables determine the economic return realized on the total investment over successive product life cycles.

(2) Transitioning *across* technology life cycles is an even more difficult issue for the policy process to address. A number of high-tech companies (for example, Intel) 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.

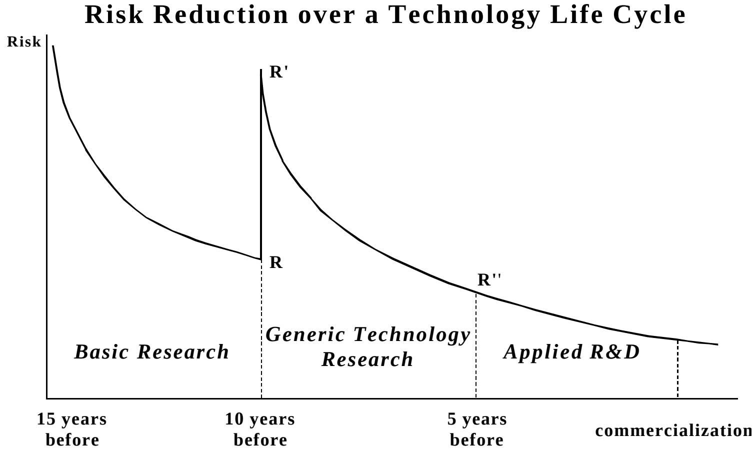
Under a Vannevar Bush-type of model, government can rationalize funding years, even decades, of basic research. At some point, enough knowledge is accumulated to allow judgements of risk associated with potential market applications of a new technology based on the underlying science. In an oversimplified model, applied technology research should be more or less automatically initiated and a new technology life cycle started.

However, a major problem for R&D policy arises at this transition from basic research to technology research. Here, for the first time, market risk assessments must be added to estimates of technical risk. Combining technical and market risk complicates corporate R&D decisions way beyond what is involved in allocating government funds for basic research.

Figure 5 indicates that technology research, with its ultimate objective of market applications, encounters an initial major increase in technical risk 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. This additional risk, RR', occurring in the early phases of the R&D life cycle, can and does act as a substantial barrier to private investment in technology research. Understanding the evolution of and the interaction between technical and market risk and the consequent impacts on private-sector investment are the key elements for effective R&D policy analysis.

Figure 5

Risk Reduction over a Technology Life Cycle



Source: Tassey [1997, p. 76]

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.
- The time between invention, innovation (first commercial use), and major economic impact (widespread market penetration) can be long, spanning several decades. However, the market transition to a new technology life cycle requires preparation and can take place in other parts of the domestic or world economy before firms using the old technology realize that change has occurred.
- A major reason that such cycle transitions are difficult is the fact that firms need complementary economic assets (skilled labor, capital, and infrastructure) to successfully develop and market new technologies. These assets may not be available and vary significantly from one life cycle to the next.

The current transition to a knowledge-based service economy is based on continuing major changes in digital electronics and the advent of complex knowledge systems based in part on that technology. These changes are requiring major adaptation by the economies of industrialized nations. The typical pattern is, once again, proving itself—many of the economic leaders of the previous technology life cycle are being left behind as the new cycle emerges. The major reason for this pattern is the tendency for existing companies to remain locked into investments in the economic assets that work in the current (defender) technology life cycle. Finally, even when entry positions in new technologies are achieved, the dynamics of a technology-based economy demand continual adaptation over the entire life cycle.

3.2. The Dual Value of an R&D Capability

Conventional wisdom actually understates the importance of R&D in technology-based industries by indicating that capital spending exceeds R&D spending. Such a relative ratio of investment has been true until recently. However, R&D has two strategically critical roles in the "knowledge-based economy": (1) implementation of internal innovation strategies, and (2) to provide the capability to absorb technology from external sources.[19]

Given the growing importance of these functions, many companies are increasingly spending more on R&D than on plant and equipment. More than one-half of Hewlett-Packard's sales now come from products the company developed within the previous two years. In 1997 and 1998, HP spent more on R&D than on plant and equipment ($3.1B versus $2.3B and $3.4B versus $2.0B, respectively). To some extent, such relative increases in R&D spending are due to the fact that high-tech firms such as HP are contracting out more of their manufacturing requirements than in the past, which reduces capital expenditures. However, such strategies only accentuate the evolution of these companies toward a focus on knowledge-based competitive advantage.

HP exemplifies the dual R&D strategy. The company is recognized as the world's leading innovator in test and measuring equipment, but one of HP's most successful products in recent years is the ink-jet printer. This product was the result of successful

[19] See Cohen and Levinthal [1989].

imitation and improvement upon the innovating firm, Canon. Canon had the patents on early ink-jet designs but made a strategic error by choosing to attempt a complex implementation that ultimately set it years behind.

HP, which licensed Canon's patents, achieved a major advance when it succeeded in moving all the electronics except one resistor off the print head and incorporating the internal baffling into the plastic mold of the print-head case itself. The result was a product of great simplicity, leading to the lowest cost print head in the industry (inexpensive enough to be disposable). In 1984, HP introduced the ThinkJet, the first ink-jet printer for the desktop market. Initially, the ThinkJet was inferior to the dot-matrix printer, and leading Japanese dot-matrix companies like Epson viewed this technology virtually with contempt.

In summary, HP was not the inventor of inkjet printer technology but could be called an innovator at the component level. The company spent a significant sum on developing an improved imitation of the original Canon technology. In 1997, HP generated over $5 billion in sales from ink-jet printers. Moreover, the success of the ink-jet gave HP skills in high-volume manufacturing, helped it establish relationships with computer retailers, and improved the strength of the company's brand name.[20]

This example clearly demonstrates the twin benefits of conducting R&D—technology absorption and internal technology development. However, R&D at the company level cannot exist in a vacuum. 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. The overall health of the entire R&D network, in turn, determines the breadth and depth of national competitiveness.

3.3. Transition to a Life-Cycle Based Economic Model

The essence of technology-based economic growth is that a body of scientific knowledge is drawn upon for the development of technologies which, to varying degrees and in various forms, eventually result in markets that contribute value added to the gross domestic product of the economy. Value added is therefore the end point for economic growth policy, and the factors determining its growth over time constitute the critical elements of policy analysis.

R&D policy has for decades suffered from a failure to incorporate the above factors and thereby improve upon the early post-war Vannevar Bush model. In such a model, science is recognized as a national resource but supports growth in GDP through a mysterious entrepreneurial process. This process transforms science into commercially viable technology through a series of steps that must be understood in order to improve the functioning of the economic system in a much more competitive world economy.

A more effective economic model of technology-based growth will incorporate four basic elements:

[20] Elias [1995, p. 12].

(1) The early phases of technology development encounter considerable technical and market risks that are often beyond the capabilities and hence the investment criteria of individual firms or even groups of firms.

(2) Efficient development of technology by industry requires a complex set of supporting technical infrastructures to evolve along with the technology itself.

(3) Transactions in technology-based markets involve sophisticated products and services, which require equally sophisticated infrastructure support.

(4) R&D investment patterns and the consequent success or failure of domestic industries in global markets is time dependent; that is, the *technology life cycle* is the dominant framework for the critical analysis of how different R&D investments are made—including the early investments that initiate the cycle across supply chains.

Corporate managers, business analysts and economists have argued over how to best represent all four elements in a conceptual economic model. So-called linear models capture the time dimension to a degree but have been appropriately rejected as too narrow in scope and overly simplistic. However, no consensus on a more comprehensive policy-relevant replacement has emerged. Other concepts, such as feedback loops and chain-link or cross-fertilization among several areas of science and technology, represent other dimensions of R&D investment patterns. Each of these concepts enables a characterization of factors in the evolution of technology through various phases in the R&D life cycle.

While each concept has its limitations, they are not mutually contradictory. In fact, they embody complementary elements of the needed economic policy model. The feedback loop seems to be an attractive concept for R&D managers, and refers to the integration of the three phases of economic activity—R&D, production, and marketing. Market experiences feed back to R&D and production, resulting in adjustments to product design and process technologies. Certain feedback loops are consciously compressed by companies—in particular, the interactions between product and process R&D that reduce manufacturing problems. This phenomenon is most prominent in shorter product life cycles. The existence of information feedback creates a concept of technological change that is more dynamic and even circular, in which the phases of R&D and subsequent market use are simultaneously changing.

Academic researchers, who are interested in a broad representation of the innovation process itself, have proposed more complicated frameworks such as the chain link model.[21] Such models not only embody interactive relationships among stages in the development and commercialization of technology, but include complementary roles of several distinctly different technologies. Here, the pattern of technological progress is ascribed more to a mating of complementary technology assets, independent of any

[21] See, for example, Klein and Rosenberg [1986].

evolutionary process. In fact, some proponents purport to show how "technological breakthroughs are just as likely to precede, as to stem from, basic research".[22]

The chain link effect occurs most prominently in the mid-length or generic technology life cycles. That is, when new generic technologies are being developed and applied for the first time, cross fertilization often occurs among heretofore separate areas of technology.

For example, HIV protease inhibitors were synthesized by chemists in the pharmaceutical industry based on understanding the structure of HIV protease as determined by biologists using physicists' x-ray diffraction techniques. Two drug companies finalized their formulations using the ultra-powerful x-ray beams from synchrotron radiation sources normally used for nuclear physics research. Today, about 35% of the running time on the Department of Energy's synchrotron radiation sources is used for this kind of structural biology. Conversely, the development of neural network computing algorithms to efficiently sort complex multi-dimensional data sets has it origins in neurobiologists' attempts to develop an understanding of the brain's structure.[23]

The example of biotechnology (text box) does not mean that technology evolves in a purely linear process. Obviously, areas of science such as molecular biology continue to advance and thereby make possible new technological applications. Moreover, the basic research producing these advancements is often influenced by the success or failure of past technological applications. As the HIV protease example clearly shows, chain-link phenomena are real and important. Feedback loops have been accentuated in recent years by corporate strategies such as concurrent engineering, rapid prototyping, and, more recently, quality function deployment approaches to managing technology development and commercialization.

Applying Alternative Models—Biotechnology

One frequently used example of the non-linearity of technological progress is Pasteur's development of the first vaccine, where both basic and applied research are characterized as being conducted at the same time. That is, Pasteur set out to solve a problem—the need to cure a disease—but at the same time he discovered some basic principles of microbiology.

However, such historical examples do not reflect the current status of the majority of research and development as a process. Today, R&D is more structured and sequential out of necessity. Somewhat specialized tools and techniques are used for each research phase by scientists or engineers with unique skills for that type of research. Moreover, technology R&D today seldom progresses very far unless it can draw on a reservoir of scientific knowledge.

Medicine is, in fact, a good example of this evolutionary pattern. Through NIH, the U.S. government sponsored basic research over a thirty-year period before the science of molecular biology evolved to the point at which a biotechnology industry could begin to evolve. It is hard to imagine that the genetically engineered drugs that are appearing with increasing frequency could have been developed by a modern-day Pasteur using trial and error methods (which is basically the way drugs were developed from Pasteur's time until the past fifteen years of biotechnology R&D).

In general, neither increases in scientific knowledge nor technological progress are particularly steady. Major advancements occur and feed a host of applications for a period of time. The process of developing these applications for the marketplace itself

[22] National Science Board [1996, p. 4-10].

[23] Richter [1998].

creates knowledge, which feeds back to stimulate a more orderly evolution of the initial breakthrough. Demand pressures and technological opportunity promote linking across heretofore separate areas of technologies.

However, the example of molecular biology and other important areas of science, such as solid-state physics, demonstrate that a linear progression of knowledge still takes place as the technology life cycle progresses.[24] The knowledge gained not only feeds back into the existing life cycle but it also eventually contributes to the subsequent technology life cycle.

Criticisms of the linear model have merit. However, the debate over whether to use such a model or to adopt one of the more sophisticated variants is somewhat artificial. In some cases, those who use a linear model typically do so for simplicity's sake. The policy analysis to be undertaken does not require a more complex representation, only acceptance of a net progression of knowledge to successively more applied levels. Most users of such linear models acknowledge that reality is more complicated. Moreover, another distinction is that the two conceptual approaches address two different steps in long-term technological change. The linear model represents a higher level of aggregation in the hierarchy of knowledge, namely broader areas of technology, than does the chain link framework that focuses on single technologies.

3.4. Elements of an Economic Policy Model of R&D

Any sound policy approach to understanding technology-based growth must satisfy two basic requirements.

(1) The first requirement is the need to define a set of elements that comprise the typical industrial technology. These elements are distinguished primarily by differences in private sector incentives to invest in them.

(2) A second requirement is that the relevant investment behavior be depicted over time because of the existence of multiple cycles that characterize private sector investment in technology research.

With these two requirements satisfied, a more accurate and policy-relevant analysis of specific market failure mechanisms is possible. Equally important, appropriate government policy responses can be constructed and matched to these market failures, thereby greatly increasing the efficiency of R&D policy.

The general elements of industrial technology that are relevant for R&D policy are depicted in Figure 6. The relevance of these elements for policy analysis derives from the fact that each needs a unique set of R&D skills, facilities, and supporting infrastructures. Each one also requires a different research time frame (especially relative to each other in the R&D cycle). Finally, each element displays a markedly

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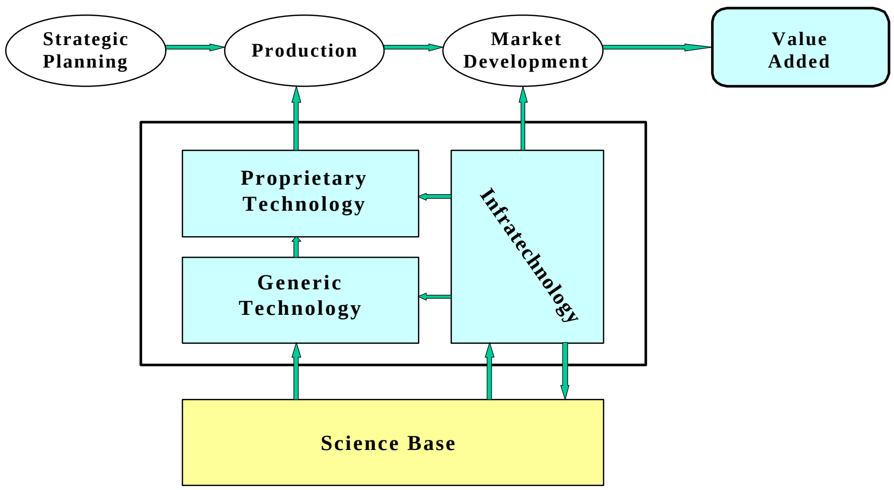
[24] In the important area of digital electronics, the transistor could never have been invented without prior knowledge of the basic science of solid-state physics, which provided the theoretical basis for thinking that a semiconducting material could be used to construct an electronic switch or amplifier. Once invented, the importance of the transistor stimulated an avalanche of further basic research making possible further cycles in digital electronics technology.

different degree or type of public good content. Thus, the sources of and processes for the development of each technology element are significantly different.[25]

3.4.1. Generic Technology. A particular science base evolves over several decades and eventually reaches a critical mass, at which point industry begins to extract commercially relevant technology from this science base. Typically, before large amounts of private-sector funds can be committed to developing market applications of the technology, the generic technical concept must be demonstrated. This necessary *generic technology research* demonstrates that the general technology may work in

Figure 6
Economic Model of a Technology-Based Industry



source: Tassey [1997, Chap. 4]

specific market applications. For many technologies, the "proof of concept" can be a laboratory prototype. Each generation of digital electronic technology (transistor, integrated circuit, multifunction chip) was first demonstrated in the laboratory and then was further developed to yield market applications over many product life cycles.

The existence of generic technology as the basis for huge amounts of follow-on private sector investment was clearly identified by Richard Nelson, but policy models have only vaguely recognized its critical importance.[26] In essence, generic technology provides general inferences about how the technology works, identifies the attributes that determine the performance of the technology, demonstrates how these attributes

[25] Economists would distinguish among these elements by applying the concepts of "rivalous" and "non-rivalous" goods. The former cannot be consumed by one individual without preventing consumption by others (e.g. toothbrush), while the latter can be collectively consumed (software). Non-rivalous goods present investment incentive problems because "free riders" consume the good but do not pay for it. However, a second condition—that of "excludability"—is necessary to determine private sector investment in non-rivalous goods. Patents, for example, are a mechanism for excluding free riders from consuming technical knowledge produced by others. Critical for R&D policy is the fact that technology infrastructure and other generic technical knowledge fall into the non-rivalous category, but excluding additional consumers of this knowledge is not in the public interest. Thus, these types of public technology goods are funded at least partially by government to compensate for spillovers.

[26] See for example, Nelson [1987, 1992].

combine to realize overall performance, and indicates initial ranges of variation for each attribute.

The broader, deeper, and more accurate the generic technology is, the greater the amount of R&D stimulated and the larger the number of market applications eventually produced. Equally important for R&D policy is the fact that generic technology diffuses to a relatively greater extent than do more applied versions of the technology. Such spillovers mean that generic technology is simultaneously drawn upon by competing companies in developing market applications. It therefore has some of the characteristics of infrastructure.

Biotechnology provides an excellent example of how generic technologies arise out of the science base, but ahead of specific market applications. The biotechnology industry is, in fact, typical of the existence of multiple technology elements and the complex relationships among them. As shown in Table 2, multiple areas of science have had to advance before a larger set of generic product and process technologies could evolve. These generic technologies have advanced over the past 20 years and are just now beginning to yield significant numbers of proprietary market applications.

Table 2
Phases in the Biotechnology Life Cycle

	Generic Technologies		
Basic Research	**Product**	**Process**	**Specific Products Developed**
▪ molecular and cellular biology ▪ microbiology/ virology ▪ immunology ▪ neuroscience ▪ physiology ▪ pharmacology ▪ genomics	▪ gene testing ▪ gene therapy ▪ gene delivery systems ▪ gene expression systems ▪ antisense ▪ apoptosis ▪ antiangiogenesis	▪ combinatorial chemistry ▪ recombinant DNA/genetic engineering ▪ nucleic acid amplification and probes ▪ gene transfer ▪ transgenic animals ▪ cell culture ▪ immunoassays ▪ monoclonal antibodies ▪ cell encapsulation ▪ implantable delivery systems	▪ protease inhibitors ▪ hormone restorations ▪ DNA probes ▪ neuroactive steroids ▪ neurotransmitter inhibitors ▪ vaccines ▪ coagulation inhibitors ▪ inflammation inhibitors

3.4.2. Infratechnology. The other category of industrial technology with significant public good content is infratechnology. Infratechnologies are a varied set of technical tools and constructs that perform a wide range of measurement, integration, and other infrastructure functions. 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.[27]

As Table 3 indicates, these 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 accuracy and high levels of quality have reached levels that a large number of diverse research-intensive infratechnologies are required—even within single industries. The resulting aggregate economic impact of these infrastructural technologies is substantial.[28]

Table 3
Uses of Infratechnologies by Stage of Economic Activity

R&D	**PRODUCTION**	**MARKET DEVELOPMENT**
Timing & Efficiency ▪ Materials Characterization ▪ Measurement Methods ▪ Techniques (design for manufacturing, rapid prototyping)	**Process & Quality Control** ▪ Process Modeling ▪ Measurement and Test Methods ▪ Process and Quality Control Techniques	**Transaction Cost Reduction** ▪ Acceptance Test Methods ▪ Interface Standards ▪ Compatibility/Conformance Test Facilities

Source: Tassey [1997, p. 158]

One indication of the pervasive and substantial impact of measurement infratechnologies has been provided by a NIST 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 is expected to continue growing at about 15 percent per year, reaching approximately $5.5 billion in 2001.[29] Thus, the cost of not having needed infratechnologies and associated standards in place can be substantial. Another NIST study of interoperability in the U.S.

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[27] Tassey [1997, Chap. 8].

[28] For summaries of microeconomic studies of infratechnologies and associated methodologies, see Link and Scott [1998] and Tassey [1997, 1999].

[29] Finan [1998]. The estimate does not include the labor and overhead required to implement this measurement infrastructure.

automobile industry found that lack of standard formats for the transfer of electronic product design data between suppliers and automobile manufacturers is costing that industry approximately $1 billion per year.[30]

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 even at the customer/vendor interface. In service industries, infratechnologies help define output, interoperability, security protocols, and intellectual property.

Infratechnologies also could include the various techniques, methods, and procedures that are necessary to implement the firm's product and process strategies. Methods such as total 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 infrastructural or public good character.

3.5. Market Failure and Underinvestment over the Technology Life Cycle

The concept of technology life cycles is particularly important for R&D policy because it implies a time order or evolutionary character—including both a beginning and an end—to various market failures that tend to appear at various points in the typical life cycle. Hence, this concept helps to determine of appropriate policy responses within life cycles as well as the critical transitions between cycles.

In general, four basic categories of underinvestment can and do occur:

(1) aggregate underinvestment by an industry (e.g., insufficient total R&D);

(2) underinvestment in applied R&D in new firms (e.g., insufficient venture capital);

(3) underinvestment in new generations of existing technology or in radically new technology (e.g., insufficient generic technology research)

(4) underinvestment in supporting technology infrastructures (e.g., insufficient infratechnology R&D)[31].

Because technology evolves cyclically, market failures that lead to underinvestment tend to repeat themselves. Moreover, distinctly different types of market failure exist and therefore require different government or industry/government response modes. In each case of market failure, the particular barrier increases the probability that the project’s risk-adjusted and time-discounted expected rate of return will not exceed a company’s hurdle rate. In such cases, where the social or aggregate economic rate of

[30] Research Triangle Institute [1999].

[31] These four categories of market failure and the appropriate policy responses are discussed in detail in Tassey [1997, Chaps. 6–10].

return is high (above society's hurdle rate), underinvestment occurs and economic growth is reduced below its potential.[32]

3.5.1. Important Characteristics of Market Failure. The following are the major types of market failure that can and frequently do occur over the typical technology life cycle.

(1) ***Technology is inherently risky.*** A certain amount of risk is reasonable given the considerable expected rewards from technology investment. However, the more radical or complex the attempted technical advance (technical risk), or the longer the time period needed to conduct the R&D during which demand can shift or competitors can commercialize the technology first (market risk), the greater the probability of an inadequate rate of return being realized.

(2) ***The benefits from technology tend to diffuse or leak to firms beyond the originator (innovator).*** Such spillovers are of two major types: price and knowledge.

   (a) *Price spillovers* occur when the market price does not fully capture the additional benefits from the new technology. That is, the user (buyer) in effect receives some of the benefits for free. Up to a point, the existence of such spillovers is desirable because, if the new technology were fully priced, the buyer would be indifferent between the old and the new technologies. Market forces determine the actual distribution of benefits. The supplier (innovator) must simply capture enough of the benefits to meet or exceed the investment hurdle rate applied to the original R&D investment decision. Under certain competitive structures, a sufficient rate of return cannot be projected.

   (b) *Knowledge spillovers* refer to leakage of the innovator's new technical knowledge horizontally to competing suppliers. This type of spillover is good for the economy as a whole, but it decreases the expected returns for potential innovators. To the extent that rates of return fall below the private hurdle rate, investment by potential innovators will not occur.

(3) ***Market Structure can reduce expected rewards from technology investment.*** An increasing number of technologies are systems. System components must interface seamlessly with other components to work effectively. That is, they must interact in a fully functional manner with minimal effort by the user (system integrator). Otherwise, the cost and flexibility advantages from having choices among suppliers of individual components (as opposed to buying turnkey systems from a single supplier) are eroded.

   Interfaces between complex components often are far from seamless, frequently being just as complex as the components themselves. In such cases, achieving compatibility or interoperability results in significant

[32] Tassey [1997, Chap. 5].

additional costs, thereby raising total system costs and lowering the expected rate of return to both the suppliers and users of the components. These costs are particularly high (and, in fact, interoperability is usually not achieved) when competing private interests attempt to provide this type of infrastructure independently. The higher cost of non-interoperable systems, coupled with reduced functionality, lowers the technology's rate of market penetration.

(4) ***Corporate strategies often are narrower in scope than a new technology's market potential.*** Some new technologies (advanced ceramics, for example) have applications in a number of markets previously served by very different technologies and hence industries. Companies in the existing industries typically do not have the strategic profile or the production and marketing knowledge to target all the potential applications (i.e., to capture economies of scope). Thus, the expected rate of return to each company is lowered relative to the risk of developing the generic technology, which applies to all potential applications.

(5) ***Increasingly dominant "systems" technologies require complex infrastructure.*** Automated production systems and technology-based services such as finance, communications, and entertainment all require sophisticated information infrastructures. Significant private investment in applications only occurs after the infrastructure is developed and implemented (for example, several decades of government support for the Internet were required before private investment in applications using it took off).

In addition to price and knowledge spillovers, network externalities are frequently labeled as a third type of spillover. However, this phenomenon does not cause a redistribution of benefits from the innovating firm to other firms. Rather, it usually results in increased benefits for all market participants. The expanding market for the network increases the value for individual network participants and therefore most likely for the original supplier (innovator). The market failure risk here is associated with the potential for network externalities to generate increasing returns to scale for the innovator. If increasing returns are strong enough, the innovator could become a monopoly and bar entry by other firms and possibly restrain innovation for some period of time.[33]

> *The scope of market failure mechanisms affecting technology-based investment is broad. Spillovers are the most frequently (and sometimes are the only) reason cited for private-sector underinvestment in R&D. However, as the above analysis indicates, spillovers are only one characteristic of technology-based competition that can lead to inadequate investment. These characteristics directly affect either the benefit or the cost side of the investment calculation.*

[33] This phenomenon is the general economic basis for the Justice Department's antitrust suit against Microsoft.

3.5.2. Transitions between Technology Life Cycles. One of the main factors causing shifts in market share leadership across companies, industries and countries is the phenomenon of transitions between successive technology life cycles that serve the same market function (e.g., computing or communications). New technologies often have very different characteristics from the old or defender technologies that they seek to replace. Hence, strategies, organizational characteristics, and R&D capabilities that work well in one life cycle are not effective in the next cycle.

An example is computing. The first life cycle's technology was manifested in the mainframe computer. Processing power was a scarce resource and hence everything was optimized to maximize the productivity of the processor. A single, huge machine was housed in an air-conditioned room, operated by technicians who strictly allocated users' access. In the second life cycle, the personal computer reversed the control of the system. The user now owned the highly dispersed processing power. Now, a third technology life cycle is emerging in which the Internet offers the prospect of a reversion to a centralized computing system. In each of these three periods, the nature of the technology, the organizations supplying it, and the interface with the user vary significantly.

> *Within each life cycle, technology evolves according to conventional market dynamics. Efficiency can be achieved* within *short-term product life cycles largely by the private sector, with modest infratechnology support from government. However, major market share shifts occur across national economies, if the original generic technology is not improved over its life cycle. Even greater shifts in competitive position occur* between *major life cycles. Failure to prepare domestic industries for the transition by advancing new generic technologies typically causes major losses in sales, profits, and jobs to foreign competition.*

4.0. R&D Trends and Market Failures

4.1. The Tenuous Nature of Competitive Advantage

Even when industry has access to a rich generic technology base for applied R&D, market success can be fleeting or never achieved. The past several decades are littered with U.S. firms and entire industries that failed to conduct enough R&D to create and sustain competitive advantage. Too many instances exist of important technologies whose development was initiated in the United States but were taken over by industries in other nations to the substantial benefit of those other nations' economies. The following are just a few examples of technology-based economic growth opportunities that have been lost by U.S. industry for a variety of reasons:

- **Semiconductor production equipment: Steppers.** The stepper was invented in the United States, but market share is now almost totally Japanese. The loss of competitive position in semiconductor manufacturing equipment not only reduces the contribution to domestic economic growth in the electronics supply chain, but it also may reduce the productivity of other levels in that supply chain (particularly, U.S. semiconductor manufacturers). These manufacturers can find themselves at a competitive disadvantage relative to their competitors in Japan, who are more closely linked to the Japanese equipment suppliers. (Solving this vertical integration problem has been the primary objective of SEMATECH.)

- **Flat panel displays.** RCA invented the liquid crystal display, but had too narrow a view of its applications and essentially gave the technology to the Japanese. The Japanese now own 95 percent of a world market that is growing rapidly and driving downstream equipment/product markets.

- **Advanced Ceramics.** The current revolution in wireless communications would not have been possible without the discovery and development of oxide ceramics. The ceramic requirements of microwave applications (e.g. filters, oscillators, resonators) are critical and these components collectively represent a majority of end-use devices. Every modern commercial wireless communication and detection system in actual use or in advanced development incorporates oxide ceramics. This important compound was discovered and its processing phase diagrams determined in the early 1970s at Bell Labs and the National Bureau of Standards, respectively. Despite these early and fundamental U.S. advances, Japanese industry today clearly dominates the production and commercial markets for these ceramics (estimated at $700 million for 1997). For example, only two U.S. companies (Motorola, which serves a captive market, and Trans-Tech, a small company with annual sales of $35 million) produce ceramic components, as compared with six major companies in Japan. Furthermore, control of this technology has stimulated additional Japanese R&D and led to most of the new materials that are enabling dramatic advances in miniaturization and performance of wireless communications equipment.

- **Robotics.** Today's industrial robotics market (worth about $6 billion) is dominated by Japanese companies such as Fanuc, Yaskawa Electric, Kawasaki Robotics, Mitsubishi Electric, and Motoman. U.S. companies—Westinghouse, General Electric, General Motors, and Unimation—first established the industrial robotics market in the 1960s but, by the mid-1980s, all had sold their robotics interests to Japanese companies. Today, the largest U.S. robotics manufacturer (Adept Technology, San Jose) employs just 375 people. The only non-Japanese robotics manufacturer of any size is the Swiss-Swedish company ABB Flexible Automation.

- **Video cassette recorder.** Ampex and RCA developed the video tape recorder (VTR) in the 1950s. By the 1980s, its descendent, the videocassette recorder (VCR), was in one-half of all American homes, with virtually all of these VCRs made by Japanese firms.

- **Semiconductor memory devices.** The United States invented the transistor and the integrated circuit. Yet between 1979 and 1986 U.S.-based firms saw their world-market share decline from 75 percent to 27 percent. After that, U.S.-based firms recovered some of this loss. However, the persistently weak U.S. position is indicated by the fact that only two of the top ten firms worldwide in the major memory circuit markets (DRAM and SRAM) are based in the United States.

- **Digital watches.** The first electronic digital watch was introduced in 1971 by a U.S. company, Time Computer, which held all the patents. The semiconductor chip that ran the watch was purchased from RCA. Today, the Japanese dominate both the component and watch markets. Even though a number of U.S. electronics companies (such as Motorola, National Semiconductor, and Texas Instruments) made significant improvements and cost reductions early in the technology life cycle, the Japanese relentlessly improved the technology and reduced its cost, thereby taking over this market.

- **Interactive electronic games.** In 1972 Magnavox developed the first interactive game designed to be played on the screen of a TV. Two years later, Atari, Inc., was formed and led the market for a number of years. Now, that market is controlled by Japanese firms.

Many argue that competitive failures such as the above examples are the fault of poor industry strategy and that the inherent efficiency of the market place demands no government interference. This view has considerable merit with respect to market applications within a single technology life cycle that result largely from applied R&D. However, if applied R&D needed no stimulus at all from government, various tax incentives such as the R&E tax credit would not be needed. Moreover, numerous data suggest that industry is increasingly under investing in two critical areas:

- Next generation technology (the technology base for the next technology life cycle) and

- The extremely varied sets of technical tools that are used to conduct R&D, control production processes, and execute the sale of complex technology-based goods and services.

4.2. Underinvestment in Generic Technology Research

Universities are the primary source of the Nation's basic science. Scientific knowledge diffuses in part through contact with industry and certain types of partnering, but mainly through new graduates in science and engineering. The next step—proving the generic technological concept, so that corporate R&D managers can make the technical and market risk assessments necessary for follow-on applied R&D investments—is much more complex. This early-phase generic technology research does not absorb a large portion of total R&D spending in most areas of technology, but its critical position in the R&D cycle means it has the potential to leverage much greater amounts of follow-on applied R&D.

Various combinations of industry, government, and universities fund or conduct generic technology research through a variety of organizational arrangements. These partnerships are attempts to deal with the quasi-public good nature of generic technologies and the consequent set of market failures that result from the mismatches between their characteristics and private-sector risk tolerances, R&D capabilities, and market strategies.

Case studies have shown that long-term, high-risk corporate research is declining.[34] In Table 4, the Industrial Research Institute survey data for "directed basic research" spending plans by industry during the 1990s supports the case studies.[35] Moreover, this research has a discontinuous character, thereby stretching out the R&D life cycle and making the eventual market applications highly uncertain. 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 exhibited many of the types of market failure described earlier in Section 3. In eight of the 11 case studies, the researchers found that government was a major source of funds

Table 4
IRI Annual R&D Trends Forecast for Industry-Funded Directed Basic Research, 1991–1999

Survey	**Percent of Respondents Increasing Directed Basic Research**	**Percent of Respondents Decreasing Directed Basic Research**
1991-1995	8–14 %	23–38 %
1996	17 %	5 %
1997	15 %	13 %
1998	14 %	28 %
1999	14 %	37 %

Source: Industrial Research Institute

after the project was formalized. For the most part, these funds were used to extend, expand, or accelerate projects. Partnering with other firms (large and small), universities, and government laboratories was a common approach.[36]

4.3. Underinvestment in Infratechnology Research

Support for infratechnology research also has been generally inadequate. For example, the budget for the NIST laboratories has grown only 2.0 percent per year in real terms in the last 24 years, 1973-97, compared with an average annual real growth rate of 8.9 percent for industry-funded R&D—the productivity of which NIST's measurement-related infratechnology research is charged with supporting. The markedly different growth rates have resulted in the NIST laboratory research budget declining by one half relative to industry R&D spending during this period.

The NIST labs provide a wide range of measurement-related infratechnologies to industry. As described earlier, these infratechnologies—either directly or through incorporation in industry standards—are pervasive in terms of their economic impacts. They leverage the productivity of R&D, enhance quality and process control, and

[34] See, for example, Corcoran [1994], Duga [1994], and Geppert [1994].

[35] This is comparable to generic technology research.

[36] Rice, Peters, and Morone [1998, pp. 57–58]. Also, see Eidt and Cohen [1997].

facilitate efficient marketplace transactions for complex, technology-based products and services.[37]

4.4. The Changing Nature of R&D and Innovation

As previously described, the various elements of the typical industrial technology are developed and combined according to the capabilities of the R&D network. Depending on the amount, composition, and overall efficiency of this process, varying amounts and types of technology will be produced in different time frames.

4.4.1. Measures of Technical Output. The output of R&D investment is technical knowledge, of which a large portion is codified in the form of patents. Recognizing that patents vary greatly in terms of their economic importance, a number of indicators have been developed recently that adjust for the importance of a patent (citation frequency) and depreciation rates (age of older patents cited), as well as the number of patents in a particular area of technology. This methodology was applied in a Department of Commerce/Office of Technology Policy study of patenting in five diverse industries/areas of technology—information, advanced materials, health (pharmaceuticals and biotechnology), automotive, and express package transportation and logistics.[38]

The results showed that, for patents granted during 1982-96, the United States led in four of the five areas of technology studied—advanced materials being the exception. A similar analysis for all patents worldwide over this time period showed that shorter life cycles and greater dependency on underlying science are broad trends. The implications of this study are:

- U.S. "technological strength," as measured by the number and quality of patents, is pervasive across diverse areas of technology;
- Technology in virtually all areas is increasingly science based;
- Technology life cycles are compressing.

Another recent analysis of patent data shows that aggregate R&D intensity does not correlate with the quality of patents, but the early research phase of R&D correlates strongly. In fact, research intensity leads to higher shares of granted patents and higher citation ratios.[39]

4.4.2. Technological Complexity. Complex R&D results in complex products and processes, and both are increasing over time. In one study, complexity was defined as "a technological process or product [that] cannot be understood in full detail by an individual expert sufficiently to communicate all the details of the process or product across time and distance to other experts".[40] Using this definition, Table 5 shows that in

[37] Tassey [1997, Chap. 8].

[38] Albert *et a*l [1998, pp. 29-41].

[39] Ernst [1998, p. 8]. "Research" is defined in this study as basic plus applied research (following the OECD definition).

[40] Kash and Rycroft [1998].

1970 and 1995 the 30 most valuable product exports accounted for 48 percent and 46 percent of total global trade, respectively. However, the *portion* of these 30 products, simple or complex, produced by complex processes almost doubled from 43 percent to 82 percent over this time period.

One implication of these data is that process technology is at least as important as product technology. In the 1980s, U.S. industry was appropriately criticized for not investing enough in process technology. This area of underinvestment led to losses in

Table 5

Thirty Most Valuable Product Exports: Distribution by Complexity in 1970 and 1995 (1995 $billions)

Simple Process/Simple Product	**Simple Process/Complex Product**
1970 = 58%, $85 1995 = 20%, $380	1970 = 0% 1995 = 0%
1970 = 12%, $18 1995 = 23%, $435	1970 = 31%, $46 1995 = 59%, $1128
Complex Process/Simple Product	**Complex Process/Complex Product**

Source: Kash and Rycroft [1998]

market share in a number of critical industries, including semiconductors, optoelectronics, and automobiles. The imbalance has been redressed to a significant extent in the 1990s, but major weaknesses still exist in critical areas such as producer electronic products, including computer parts. In such areas, production technology in other nations is sufficiently advanced that, when combined with low-cost labor, the value added from these levels of the U.S.-based electronics supply chain ultimately moves abroad. More alarming are newer technologies, such as digital displays, which have been devastated by inadequate production technology.

4.4.3. Technological Complexity and Market Dynamics. Technical complexity generates several of the market failures cited earlier and has led to inadequate private sector R&D investment. In addition, the impact of these barriers often is increased by interactions with equally complex product structures and their markets. These additional barriers result in large part from the difficulties in integrating complex technologies that come out of the R&D process with other categories of corporate investment as well as with external market forces.

One of the most important causes of this interaction problem is the fact that key technologies are *systems* and therefore require multiple integrated component technologies and complex organizations to implement and manage these systems (examples include factory automation and communications networks).

Unfortunately, corporate R&D is shifting away from more radical objectives, which typically require both complex and multidisciplinary R&D. Such R&D is distinctly different from the dominant (in terms of funding) applied R&D. This difference means that the conventional corporate investment decision process does not work well. Such dysfunction is critical because more radical technology research is the type of R&D that yields the highest rates of return in the long run.

Example of a Complex Technology

The artificial hip joint is a complex technology requiring multidisciplinary research. Each year, loss of mobility has led over 90,000 people in the United States replace their hip joint with an artificial one. The technology has slowly advanced, extending both the life and function of implanted joints. However, functionality and reliability remain limited. For example, hip implants can become loose, necessitating another operation. One of the major causes of this problem is an unwanted stimulation of the immune system in reaction to the implant. Over a period of time the implant wears, leaving tiny particles that cause the immune system to attack the surrounding natural bone. The bone erodes, loosening the joint.

Continued improvement of hip implant technology requires an R&D process involving orthopedists, spectroscopy and measurement device manufacturers, hematologists, toxicologists, immunologists, chemists, and metallurgists. Even before the mechanical design of a new artificial hip joint can be attempted, biomaterial and chemical engineers have to find suitable materials from a wide range of candidates.

For example, new polymer and nonmetallic coatings are receiving considerable attention because of their ability to lower the coefficient of friction and hence wear rates of the prosthesis. In addition, porous outer coatings are being investigated because they offer potentially greater bonding between the prosthesis and the surrounding bone and tissue, enabling the joint to achieve a closer fit. Similarly, ceramics, glass ceramics, and composites are being studied because of their ability to bond with bone.

Individual firms are typically not equipped to coordinate, let alone conduct, such broad, multidisciplinary research. Investors also perceive the high risks in conducting and synthesizing the research required to advance multiple technologies to the point at which a mechanical engineer or an orthopedist can design the actual artificial hip joint. Equally important, the development of radically new technologies requires considerable *generic* technology research. This early-phase research requires a very different strategic planning, research management, and organizational environment, and it must be successfully completed before conventional applied R&D investment mechanisms, focusing on market applications, can take over.

4.5.3. The Time Factor. The above market failures arising from technological complexity and its effects on corporate decision making are made worse by shifts in corporate strategy and industry structure in response to growing global competition. As more nations adopt technology-based strategies which entail both external technology acquisition and internal technology development, more competitors for U.S. industries are appearing. This increased competition is good for consumers because it provides a wider range of new products and services. Also, with more companies worldwide investing in technological innovation, the products and services appear sooner.

These competitive pressures are requiring reductions in *product* cycle time—defined as the time from receipt of customer order to delivery. In a survey by NIST's National Quality Award Program, 79 percent of responding CEOs cited cost and cycle time reduction as a "major trend" affecting their company.[41] U.S. companies have managed to reduce product cycle times substantially. A National Planning Association study of 189 companies found that in 1990 new products or major product improvements took 35.5 months to complete (from concept to production), but in 1995 this time had shrunk to 23 months.[42] In another

[41] This report and other impact assessments of the National Quality Program are available at http://www.quality.nist.gov/crit2.htm.

[42] Cappelli [1997].

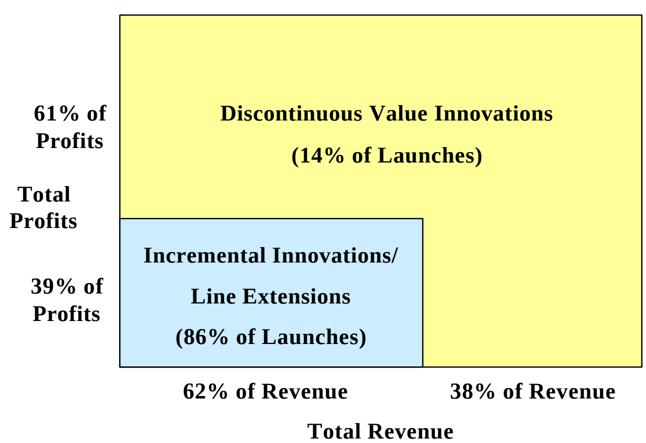
study, sponsored by the Manufacturing Institute, approximately three fourths of U.S. manufacturing companies reported shorter total cycle times.[43]

Technology has been a major investment vehicle for achieving both cycle time and cost reductions. In the Manufacturing Institute study, these two objectives were cited by three fourths of responding manufacturing firms as the major benefits of investment in technology. However, total cycle time compression also has forced a shortening of R&D cycle time. An annual survey by Carey Curtis in conjunction with the Industrial Research Institute has found that the average R&D cycle time has shrunk from 18 months to 10 months in a five-year period (1993-1998).

> *This reduction in cycle time has been achieved not only through increased efficiency. Much of the reduction is due to increased emphasis on incremental research objectives in order to meet shorter time-to-market requirements. Survey data indicate that, in some industries, shorter product R&D cycles have led to quality and reliability problems and lower financial performance.*[44]

Figure 7

Profit Differentials from Major and Incremental Innovations



Source: Kim and Mauborgne [1997]

In contrast, major technological advances take more time and entail more risk than do incremental change and improvements. More radical R&D often is contracted out or accomplished through partnering; both options lengthen R&D cycle time. Yet, as the Curtis data and a study by Kim and Mauborgne (see Figure 7) clearly indicate, longer term R&D projects are more profitable.

4.5. Innovation vs. Technology Use

Even within an R&D-intensive industry, growth in value added typically is driven by a relatively few innovative firms. Technological innovation is concentrated even though new technologies give rise to entirely new industries with substantial employment. The software industry, for example, barely existed 15 years ago but today employs over 500,000 workers. Studies of employment growth by Cognetics, Inc. have shown that even though most net new jobs (84% in the 1992-96 period) come from small firms (<100 employees), growth in employment is highly skewed among these companies.[45]

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[43] Swanidass [1998, p. ix].

[44] Ellis and Curtis [1995].

[45] Birch, Haggerty, and Parsons [1997].

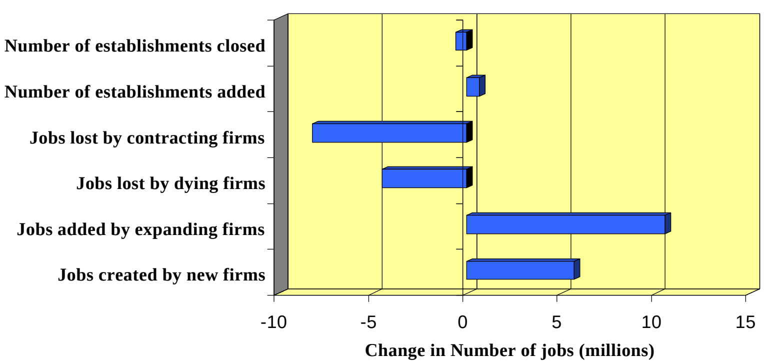
In other words, most small businesses do not create large numbers of jobs. Rather, a small number of fast growing small companies ("gazelles") account for the majority of net new jobs.

Gazelles are defined as companies whose sales have grown at a compound annual rate of 20 percent or more for four years in a row (which means they have doubled in size). These gazelles are responsible for creating about 70 percent of the net new jobs in the U.S. economy between 1992 and 1996, yet they account for about 3 percent of the 9 million enterprises in the Cognetics database (corporations, partnerships, and proprietorships). Gazelles are distributed evenly across all sectors of the economy.

Another study by the Department of Commerce of employment trends in individual manufacturing plants found that only a minority exhibited strong and persistent employment growth over extended periods of time.[46] These "heroic plants" yielded net employment gains four times the rate of manufacturing plants in general. Such plants were above average users of advanced technology and best practice, and appear to have benefited from investing in new technology early in that technology's life cycle.

Figure 8

Volatility in Employment Growth, 1994-95



Source: Census Bureau, Progressive Policy Institute

Together, these studies indicate that only a relatively few companies or even individual establishments are going to be successful innovators and users of technology and best practice, and therefore a diversified economic structure is necessary to develop enough of these "engines of growth" to drive national economic prosperity.[47]

Who these companies are will change drastically over time. The 1990s have seen steady job expansion in the U.S. economy. However, these net gains mask considerable churning in various sectors; many jobs have been created and also destroyed. Figure 8 shows this pattern quite clearly. For one yearly change, 1994-1995, almost 700,000 business establishments were added to the economy while slightly less than 600,000 ceased operating. New firms plus expanding ones created 16.2 million jobs, but firms that went out of business and those contracting caused 12.7 million jobs to disappear. All together, 30 percent all jobs in the U.S. economy were in situations of flux—i.e., they were in appearing, disappearing, expanding, or contracting firms.

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[46] Musick [1998].

[47] Unfortunately, these studies do not identify the source of the technology associated with "gazelle" or "heroic plant" performance. That is, to what extent do these plants obtain technology from a parent firm as opposed to external sources in their supply chain?

The limited number of highly successful companies and their distribution across the economy, combined with evidence that technology is a major factor in their economic success, argue for a much broader technology basis for the U.S. economy in order to maximize the number of such companies over time.

5.0. Policy Implications

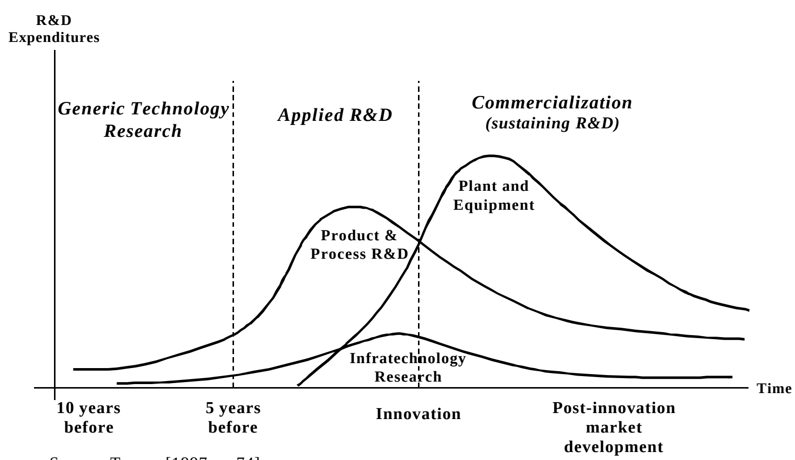
Corporate R&D investment decisions do not take place in a vacuum. They are driven by "the invisible hand"—perceived technological and market opportunities—as well as by "the invisible foot"—the threat of competition. In addition to these factors, investment decisions are also strongly influenced by the breadth and depth of a supporting technological infrastructure. Major elements of this infrastructure are:

- the availability of skilled workers;
- access to generic technical knowledge and external scientific and engineering research capabilities;
- the existence of a set of technically complex infrastructures including science and engineering data bases, measurement and test methods, interface standards, and quality assurance procedures.

The first of these is a well-defined policy issue and fortunately is now getting focused attention by policy makers. However, as described in this report, the second and third elements are complex and not particularly well understood. Thus, effective policy development remains constrained.

Figure 9

Relative Expenditures by Phase of R&D over Technology Life Cycle



Source: Tassey [1997, p. 74]

5.1. The Relative Size and Impacts of Government-Funded Research

Figure 9 indicates that amounts spent on generic technology research and infratechnology research between the 10^{th} and 5^{th} years before commercialization are relatively small. However, significant risk reduction in terms of advancing the generic technology to at least proof of concept or laboratory prototype often is essential to stimulate the much larger applied R&D investment by individual companies that eventually brings products, processes, and services to market. The acceleration of industry R&D spending over the average R&D life cycle is pronounced. Industry spends 4.4 times as much on applied research as on basic research and 2.7 times as much on development as on applied research.[48]

5.2. Patterns of Risk, Market Failure, and the Government Response

5.2.1. Matching Market Failure and Policy Response. Section 3 identified four major categories of market failure. Each requires a very different policy response.

(1) ***Aggregate underinvestment by an industry—insufficient total R&D.*** This problem is the result of either excessive risk avoidance due to adverse macroeconomic conditions or inadequate R&D capability (which raises entry costs and hence risk). Tax incentives can be effective as long as the R&D being targeted is comparable to the type already pursued by industry—that is, as long as the normal corporate R&D investment decision criteria can be applied. In other words, a tax incentive can stimulate more of the same type of R&D already conducted.

(2) ***Underinvestment in the formation of new firms—insufficient venture capital.*** Venture capital is plentiful in the United States and available for most areas of technology, once the generic technology is sufficiently advanced to allow the private sector sources of venture funding to make assessments of both technical and market risk. The policy issue is how to get to that point. A government role in advancing generic technology research has been accepted in the United States only in a few situations where an industry deemed necessary to achieve a major social objective is either inadequately structured or not formed at all. That is, if a new technology has large potential social as well as economic benefits, is not capital intensive (it can be supplied by small firms), and is radical enough to inhibit investment by large firms focused on the existing technology, then R&D policy can consider subsidizing the creation of a new industry structure as a policy objective.

Biotechnology is an example of a radically new technology that meets these criteria. The National Institutes of Health (NIH) therefore funds some applied research in small biotech firms. The Small Business Innovation Research (SBIR) Program was created to fund research in new technologies that are both socially and economically important. In such cases, funding R&D by young, development-stage companies can expand both the number and variety of such firms.[49] However, from an economic growth perspective, such policies for one or two industries will be highly inadequate in the evolving world economy.

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[48] National Science Board [1998, Appendix Tables A 4-7 and A 4-11].

[49] Small firms now get a lot of NIH funding, both through the SBIR Program and otherwise; but, prior to SBIR they did not. In fact, Congressional hearings in 1978 documented the fact that NIH had no research contracts with small business at that time.

(3) ***Underinvestment in new generations of existing technology or in radically new technology—insufficient generic technology research.*** Because of the highly microeconomic character of technology development, and hence the uniqueness of the sets of market failures that affect individual technologies, broad R&D incentives, such as a tax credit, are generally not effective. Tax expenditures tend to leak to both technologies and phases in the R&D process for a particular technology that do not require government support.[50] Instead, the efficient policy response would combine direct funding of generic technology research with appropriate joint strategic planning among government, industry, and universities.[51]

Early-phase, generic technology research often is conducted through a variety of partnership mechanisms, because this approach allows a more effective combination of research skills and facilities, pools risk, and increases the rate of technology diffusion. All nations with technology-based growth strategies have industry-government programs to cooperatively advance the early phases of a variety of technologies with considerable economic potential.

(4) ***Underinvestment in supporting technology infrastructures—insufficient infratechnology R&D.*** Infratechnologies not only have common use characteristics (including their use as standards), but they often derive from a different science and generic technology base than does the core technology being applied by industry through its internally funded R&D. The latter fact argues for a strong role by government laboratories in the conduct and diffusion of infratechnology research. Government labs can realize economies of scale and scope from unique research skills and facilities that can be applied to meet the infratechnology needs of a number of industries.[52] These labs also can provide neutral third party facilitation of the standards process.

5.2.2. Responding to technical and Market Risk Barriers. As described earlier in this report, the intrinsic technical and market risk faced by R&D firms varies over a technology's life cycle. Therefore, both industry and government responses to imperfections and resulting underinvestment in R&D and/or slower market penetration by the new technology also must vary. Figure 10 indicates how a set of existing policy responses can be used to mitigate market failures over the different phases of an R&D life cycle.

For example, after basic research has gone on for some time, the accumulated level of knowledge begins to spark interest by industry in the possibility of developing technologies based on this science. Diffusion of the basic science and subsequent initial evaluation of its economic potential can be facilitated through graduates of universities and entities such as the National Science Foundation's Science and Technology Centers and Engineering Research Centers, where industry and university researchers can

[50] Tassey [1997, pp. 107-111].

[51] Tassey [1997, Chap. 7].

[52] Tassey [1997, Chap. 8].

interact. For specific areas of technology, industry-operated entities such as the Semiconductor Research Corporation (SRC) fund research under a similar format. More recently, the Focus Center Research Program (FCRP) was established as a network, including the U.S. semiconductor industry, the U.S. Government, and 14 universities.

Diffusion of basic scientific knowledge through mechanisms such as the NSF centers and the FCRP can provide industry with an indication of an emerging technology's potential. However, as discussed in Section 3, the decision process for investing in the early phases of technology research is a difficult one for individual companies to manage effectively. There are several reasons for this difficulty:

- competitive pressures of fighting for market share in the current technology life cycle consume corporate energies;
- corporate management applies different decision criteria to long-term projects compared with the bulk of corporate R&D;
- recognition of the extremely high technical and market risks associated with a potential technology whose concept has not been proven even in the laboratory;
- R&D capabilities needed to launch a significant research program in a new technology, especially involving multiple research disciplines and laboratory facilities, are frequently incomplete within individual firms.

Even with new R&D management approaches such as options pricing techniques, these factors can combine to raise overall risk to prohibitive levels.[53] The lack of appropriate R&D capability relative to the skills and facilities required for pursuing development of emerging technologies increases risk substantially beyond that associated with an immature state of development. This latter factor is especially important when new technological opportunities require combining several heretofore separate areas of scientific or technical knowledge.

The result is the large jump in overall risk from R to R' in Figure 10. This combined technical and market risk must be reduced to levels that fit within conventional R&D decision criteria—that is, those criteria applied by companies to the majority of candidate R&D projects.

In response, risk pooling is a common strategy for conducting early-phase technology research. Consortia are widely used for this purpose in advanced economies.[54] A number of cooperative organizational forms can be used to share costs and complementary R&D capabilities. National laboratories and research institutes frequently participate in research consortia because they have the time horizons, the multiple disciplinary skills, and the unique research facilities to undertake generic technology research.

Cost-shared research consortia with various combinations of industry, government, and universities as partners are the efficient approach to conducting much early-phase

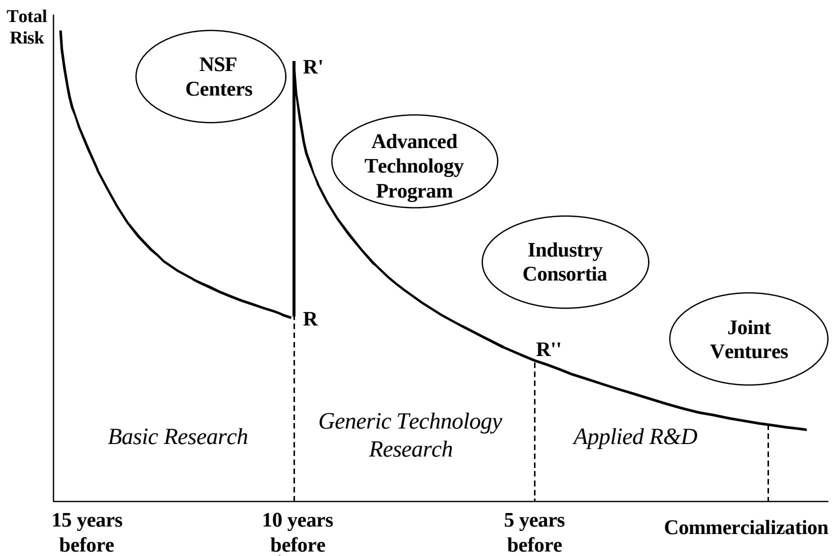
[53] For an overview of these new R&D decision techniques, see Luehrman [1998].

[54] Vonortas [1997] provides a comprehensive overview of cooperative R&D.

generic technology research in the United States. NIST's Advanced Technology Program (ATP) stimulates investment in generic technology through cost-shared industry/government partnerships. Similar but larger programs include the European Framework Program and Japan's Industrial Science and Technology Frontier Program

Figure 10

Risk Reduction over an R&D Life Cycle



Source: Tassey [1997, Chap. 7]

and its System to Support Development of Creative Technology for New Industries. As portrayed in Figure 10, such programs focus on generic technology research, i.e., early-phase research where economies of scope, long time to expected commercialization, R&D capability mismatches, and related factors inhibit corporate R&D investment decision making.

Once beyond this early-phase, industry can usually apply conventional R&D decision criteria and take on most of the applied research and development required to take the generic technology to commercialization. Figure 10 indicates that firms also will use consortia for applied research. However, such industry-led consortia seldom have a time frame of more than five years, with three to five years being the typical range.[55] Scientific research programs are typically at least 10 years long and often span several decades. Proof of concept through generic technology research often begins 5 to 10 years before commercialization. In other words, this period in the R&D life cycle can constitute a funding "gap" between basic research—largely a public good—and applied R&D—largely a private good. This "valley of death" is described by Congress in the widely discussed "Ehlers' report" as a "widening gap between federally-funded basic research and industry-funded applied research and development".[56] Government programs such as ATP attempt to help fill this gap.

[55] Mowery [1998, p. 39].

[56] *Unlocking Our Future: Toward a New National Science Policy*. A report to Congress by the House Committee on Science, September 24, 1998.

5.3. Tax incentives vs. Direct Funding

Risk aversion by the private sector with respect to aggregate investment in proprietary R&D occurs frequently and can persist for some time. Such broad-based underinvestment in R&D can be treated by tax incentives aimed at leveraging existing private-sector R&D investment strategies. The R&E tax credit has been the primary policy response for the past 17 years, and is now estimated to cost about $2 billion annually.[57]

The credit was designed to stimulate a targeted portion of overall R&D—the early ("experimental") phases that entail the higher levels of risk.[58] However, in practice, a large portion of R&D conducted by industry ends up eligible. Whether this result is good or bad is a different issue from the feasibility of using tax incentives to foster specific types of R&D. What it does show is the difficulty in targeting a tax incentive to achieve specific R&D policy goals.

In fact, specific tax incentives cannot be efficiently tailored to each technology's unique set of development and utilization barriers. Nor can they be easily altered over time to meet the funding requirements of individual technological life cycles. Thus, this policy instrument will generally not be effective as a response to market failures associated with the need to prove generic concepts underlying emerging technologies or the need to develop a range of infratechnologies to form the bases for industry standards. Tax incentives provide a general R&D investment incentive and thereby tend to increase the same kind of R&D that industry already is doing.[59]

For underinvestment in generic technology and infratechnology research, direct government funding and performance of R&D in partnership with industry and universities allows funds to be allocated to different technologies at appropriate points in these technologies' life cycles—and to these technologies only at those points. Tax incentives cannot be started or stopped based on the evolutionary pattern of a particular emerging technology. Attempts to focus a tax credit or deduction on emerging technology research will leak, as does the current R&E tax credit, into conventional applied R&D that needs no incentive.

One frequently proposed remedy is to target a tax credit at an institutional mechanism that is used for the desired type of research. Because consortia or joint ventures are commonly employed to conduct early-phase research, focusing incentives on that general mechanism arguably is one way to reduce leakage of the incentive to other types of R&D. However, the more targeted the tax incentive the more difficult it

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[57] By comparison with this tax expenditure, the SBIR Program allocates over $1 billion in R&D funds. The Advanced Technology Program has a much smaller budget of approximately $200 million. However, ATP receives considerably more scrutiny in terms of its appropriate roles and effectiveness than do the other two.

[58] For a good analysis of the R&E tax credit's structure and alternative structures, see Whang [1998–1999].

[59] In fact, the 1996 Industrial Research Institute annual survey found that 55 percent of responding companies indicated that the credit was "not at all" influential in establishing the *level* of their companies' R&D investment.

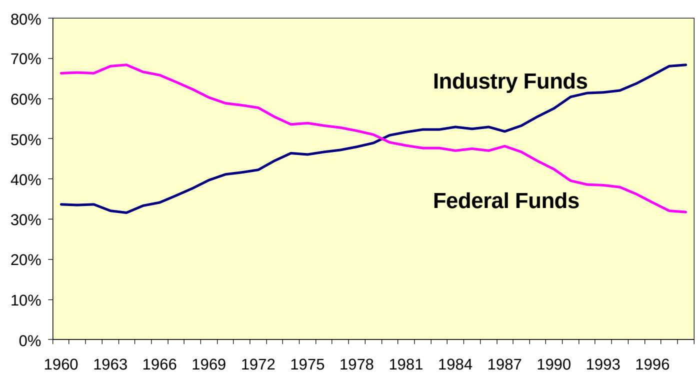
is to implement effectively. The Internal Revenue Service spent many person months in the 1980s trying to write tax rules implementing the original credit, which was reasonably broad-based in scope. Defining what is actually the coverage of a tax incentive and then enforcing it always will be a problem.[60]

Direct government funding can more efficiently leverage private-sector investment in research focused on the early phases of a technology's development. A more optimal amount and type of research can be supported and, once this research reduces technical uncertainty to a level sufficient to allow industry to begin to apply conventional R&D investment criteria, the support can be terminated.

The perceived weakness of direct funding is that government must select candidate technologies—the so-called picking winners and losers problem. However, not only does the complexity of market failures found in technology-based industries argue for the use of this mechanism, but institutional mechanisms are readily available to objectively and judiciously select research areas and determine the timing of financial support. The main mechanism for achieving this result is cooperative strategic planning between industry and government, combined with ongoing review of a project's progress and post-project impact assessment. All industrialized nations have direct funding programs and most emphasize cooperative research mechanisms.

Figure 11

Industry and Federal Shares of U.S. R&D Funding: 1960-1998



source: National Science Board [1998, Appendix Table 4-5]

5.4. The Federal Budget

As Figure 11 indicates, federal funds have accounted for a progressively smaller fraction of the Nation's overall R&D spending. Part of the decline in the government's share is due to decreasing defense spending on R&D. Another major factor is the overall decline in government spending resulting from more conservative fiscal policies. A third and most troubling factor is the lack of a consensus as to the legitimate role of government funding for different types of research.

5.4.1. The Federal Non-defense R&D Budget. At the national level, the portion of the federal R&D budget directed toward economic goals is the most relevant for R&D policy analysis. As Figure 12 indicates, federal non-defense R&D spending in constant dollars has increased steadily from a low point in FY1983 of $18.6 billion to a projected

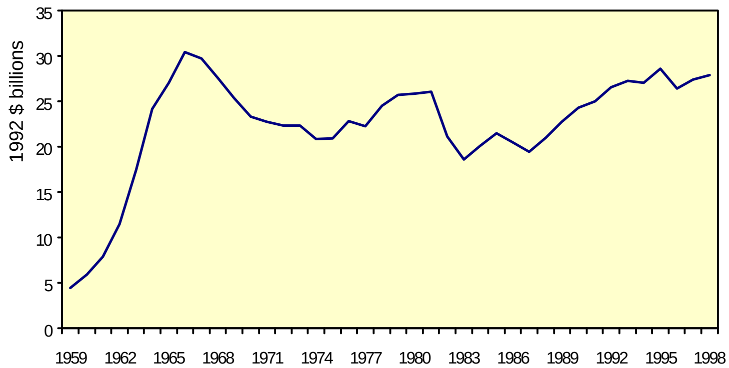
[60] Tassey [1995; 1996; 1997, Chap. 6]. The current credit does not exclude collaborative R&D. However, the magnitude of the difference between existing provisions and current proposals is not sufficiently large to provide significant new incentives.

$28.8 billion in FY1999. However, even with this growth, federal non-defense R&D has not reached the peak year's constant-dollar level of $34.4 billion in FY1966.[61]

Furthermore, the non-defense budget is highly skewed toward health care in both amount and growth rates. In particular, a significant imbalance has evolved between health care and other areas of science lumped together as "General Science," relative to their respective contributions to the economy. From 1990 to 1998, health R&D grew by 26 percent (in constant 1992 dollars), while all other non-defense areas grew by just 3 percent.[62] In FY1998, health care research received 40 percent of the Federal non-defense R&D budget and the health care sector (pharmaceuticals plus health services) accounted for 6.3 percent of GDP. In contrast, general science research (which covers most other high-tech industries) received only 9 percent of the non-defense R&D budget while accounting for about the same share of GDP.

Figure 12

Federal Non-Defense R&D Funds, FY1959-1998



source: NSF's *National Patterns of R&D Resources 1998* and historical tables

Federal R&D policy has not responded to contemporary corporate R&D trends and practices. In particular, R&D policy has not adapted to the decline in corporate generic technology research. The economics of generic technology research implies an increased role for government funding and the need for federal laboratories to focus more resources in this area. In this regard, support for government funding of generic technology research has been tepid and has lagged behind competitor nations. Comparing NIST's Advanced Technology Program (ATP) with Europe and Japan shows that competitors of the United States have much larger national programs (relative to the size of their economies) for funding this early phase research in support of economic growth.[63]

The previous example of optoelectronics is a good illustration of declining government support for critical technologies. The United States is still competitive in the applications end of this supply chain. However, not only has much of the front end of this supply chain been lost to foreign competition, but government's share of overall R&D funding has declined from 23 percent in 1991 to 10 percent in 1996.[64] Without the

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[61] The Federal Budget for fiscal year 1999, Historical Table 9.8. By a different taxonomy, the National Academy of Sciences (NAS) arrives at a "Federal Science and Technology (FS&T) budget of $33.0 billion for 1997.

[62] National Science Board [1998, p. 4–45].

[63] Tassey [1997, pp. 119–129].

[64] Bureau of Export Administration [1998, p. IV-2].

type of microeconomic analysis described earlier in this report, one cannot identify what the right amount should be, but ignoring the warnings signs will not likely result in more value added by U.S. firms.

6.0. Summary

Two broad technological and economic trends dominate all others and therefore have significant policy implications:

(1) The factors that have leveraged corporate profits in the 1990s have diminished in terms of their potential future impact, and therefore future growth depends on substantial changes in economic growth strategies; and

(2) Technological opportunity and its dominant effect on global economic growth will continue to expand.

In the context of these trends, the two important units of technology-based economic policy analysis are (1) the industry supply chain and (2) the technology life cycle. An economy is made up of a large number of supply chains, but only a relatively few can be labeled high-tech. High-tech industries account for about 7 percent of GDP. Although a number of other industries have moderate R&D intensities, the rest of the economy for the most part relies on external sources of technology, in particular, high-tech industries—both domestic and foreign. Moreover, domestic R&D is not only concentrated on an industry basis but geographically as well.

R&D displays a life cycle pattern and investing in it therefore presents different sets of investment barriers at different points in time. The life cycle concept is important, even though many feedback loops within technology trajectories occur and much technology development depends on cross-linking among several areas of science and technology.

The barriers to adequate investment across supply chains and over technology life cycles can be collected into two major problem areas. First, industries adopt technologies with varying degrees of completeness and efficiency. They are therefore susceptible to market share loss by increasingly technology-intensive foreign competition. In such situations, the contribution to the economy of entire supply chains can be greatly reduced or even eliminated over time. Second, the high-tech sector is too small to drive acceptable rates of economic growth by itself, and major elements of this sector are demonstrating a shortening of R&D investment time horizons. Even more worrisome for the long run is a pervasive problem for R&D firms in transitioning investment strategies to new technologies. Together these market failures are resulting in loss of competitive position at specific levels (industries) in technology-based supply chains. Only the more narrowly defined version of high-tech trade still shows a trade surplus. Two decades of deficits in the much broader merchandise trade balance provide ample evidence of the aggregate decline in overall competitiveness.

Long-term economic growth strategy must be based on a much more pervasive technology-intensive sector. Achieving this objective will not be easy because of continually declining corporate investment in generic technology and inadequate investment in appropriate technology infrastructures. Remedying these problems will require a much more enlightened R&D policy framework.

Specifically, effective R&D policy development requires a more detailed specification of the range of market failures that occur in technology-based industries. Appropriability problems, for example, occur to some degree through a variety of mechanisms in the life cycles of all technologies. The manifestation of appropriability problems is the leaking or spilling over of technical knowledge to parties who do not pay the creators of this knowledge its full value. Such spillovers lower the expected rates of return from investment in technology and thus act as a disincentive to private-sector R&D spending.

What complicates R&D policy analysis is the fact that spillovers occur in several ways and at several phases of the R&D life cycle. Moreover, other types of barriers to acceptable private rates of return, such as market structure and transaction cost barriers, frequently occur. Thus, a broader market failure taxonomy is needed, one that includes the following categories:

- **emerging** technologies that entail high risk and long gestation periods but create new markets with significant value added;
- **systems** technologies that provide infrastructure to many product and service technologies and thereby drive growth in major economic sectors;
- **enabling** or multi-use technologies which benefit multiple segments of an industry or group of industries, but encounter economies of scope and diffusion investment barriers;
- **infratechnologies** which leverage investment in both development and use of proprietary technologies, but which require distinct competencies to develop and common ownership (such as standards) to effectively use.

For these classes of technology, the evolutionary patterns of technical and market risk over the relevant life cycle can and do result in inadequate investment a key points in the life cycle. Based on the range of data gathered for this report, three particularly important negative impacts of these market failures are:

(1) ***Corporate investment decision dysfunction with respect to longer-term, complex, and multidisciplinary technology research.*** Underinvestment is particularly pronounced in the early phases of the R&D life cycle, which most strongly exhibit the investment barriers resulting from the intrinsic *technica*l risk of the technology and its mismatches with existing corporate strategies and competences.

(2) ***Excessive compression of R&D life cycles with resulting disincentives to undertake long-term, high payoff research.*** Global competition is forcing shorter total product life cycles which, in turn, are forcing corporate R&D portfolios to overemphasize product-line extensions and incremental process improvements. In general, less *market* risk is assumed by the private sector.

(3) ***Failure to project access to the markets for increasingly system-based technologies.*** Many of today's most important technologies have complex system structures, which require equally complex interfaces to enable market entry by small and medium suppliers and system optimization by users. Without the needed infrastructure, inefficient industry structures evolve.

The major technology trends identified in this report obviously have implications for the amount and type of R&D needed to achieve steady, high rates of economic growth. Equally important, technology trends interact with corporate strategy, industry structure, and government policy (in particular, policies that provide technical infrastructure at the various phases in a technology's life cycle). Technology trends or trajectories, once established, can have dramatic effects on a number of industries or even sectors of the economy in terms of both rate and directions of growth. Hence, early evaluation of the multiple trajectories usually afforded by the timely development of generic technology is essential.

Given the nature of technology market failures and the significance of rectifying them, the two major R&D policy issues facing the U.S. economy today are

(1) ***Understanding and providing appropriate policy responses for the early phases of technology research.*** Efficiently bridging the valley of death—the widening gap between federally funded basic research and industry-funded applied research and development—does not require large amounts of federal funding. However, this funding for generic technology research is essential to lowering the substantial technical and market risks typical of early phases in a technology's life cycle and must be available when the window of opportunity is open. All industrialized nations have or participate in industry-government partnerships of various forms to provide this essential category of technology infrastructure.

(2) ***Identifying and providing technical infrastructures needed by technology-based industries.*** The needs for these infrastructures vary over the typical technology life cycle and have strong public good content, thereby requiring effective government support. As with generic technology, research support for the needed range of infratechnologies requires relatively modest amounts of funding. However, this funding must not only be adequate, but it needs to be directed to unique research facilities that can achieve the large economies of scale and scope that characterize this type of technology infrastructure and that can also efficiently diffuse it to industry, standards organizations, and other users.

The bottom line is that R&D policy and long-term economic growth policy must become much more of a co-evolutionary system in order to achieve the synergies needed for a competitive, technology-based economy.

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