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Rationales and mechanisms for revitalizing US manufacturing R&D strategies

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Abstract The race to economic superiority is increasingly occurring on a global scale. Competitors from different countries are employing new types of growth strategies in attempts to win that race. The United States cannot, therefore, continue to rely on outdated economic growth strategies, which include an inability to understand the complexity of the typical industrial technology and the synergies among tiers in high-tech supply chains. In this context, a detailed rationale is provided for maintaining a viable domestic technology-based manufacturing capability. In the United States, the still dominant neoclassical economic philosophy is at best ambivalent on the issue of whether a technology-based economy should attempt to remain competitive in manufacturing or let this sector continue to offshore in response to trends in comparative advantage, as revealed through shifts in relative prices. The paper argues that the neoclassical view is inaccurate and that a new innovation model is required to guide economic growth policy. Specifically, the paper provides (1) a rationale for why an advanced economy such as the United States needs a manufacturing sector; (2) examples of the process of deterioration of competitive positions for individual industries and, more important, entire high-tech supply chains; (3) an explanation of the inadequacy of current economic models for rationalizing needed new policy strategies; and (4) a new economic framework for determining both policy mechanisms and targets for those mechanisms, with emphasis on the systems nature of modern technologies and the consequent requirement for public–private innovation ecosystems to develop and deliver these technologies. Several targets are suggested for major policy mechanisms.

Keywords Innovation economics · Economic growth policy · Manufacturing · Innovation policy models · Policy mechanisms

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1 The problem statement

US manufacturing's competitive status is increasingly challenged by other economies. Established industrialized nations such as Japan, Germany, Korea and Taiwan are developing state-of-the-art technologies, which range across all areas of manufacturing from electronics to discrete parts. Products based on technologies that originated in the US economy, such as semiconductors and robotics, are increasingly both developed and produced elsewhere. Emerging economies, such as China, are acquiring manufacturing capability through modest R&D intensities, tax and other incentives for foreign direct investment, and intellectual property theft. This second group then competes through low-cost labor and the use of exchange rate manipulation along with tariff and non-tariff barriers.

However, emerging technology-based economies have the long-term goal of attaining world-class status as innovators, which means they are not content to operate in the low-technology, labor-intensive portion of manufacturing. China already is producing 30,000 patents annually and its patent application rate trails only the United States and Japan.[1] Finally, event the huge US lead in biopharmaceuticals is now under attack, as an increasing number of economies invest in supporting science and technology infrastructures and provide financial incentives for foreign direct investment in this rapidly expanding technology.

The combined long-term impact on the US economy of investments by both established and newly industrialized economies has been the offshoring of substantial portions of US manufacturing supply chains—first the labor-intensive industries but now the high-tech ones, as well.

Technological convergence is occurring across the global economy even though the US manufacturing sector has become somewhat more high-tech over the past three decades. The reason is that "more high-tech" is a relative term in that US manufacturing's average R&D intensity has increased over a 25-year period from 2.6% in 1983 to 3.7% in 2007. However, this ratio is still well below the R&D intensities of truly high-tech industries.[2] Moreover, part of this modest increase is due to the offshoring of the lowest R&D-intensive manufacturing industries, rather than to absolute increases in R&D spending by the remaining domestic industries.

The importance of the development or acquisition of technology combined with its effective utilization cannot be overstated. Economic studies over several decades have demonstrated the essential role of technology in economic growth. Essentially, the high-income economy must be the high-tech economy. However, larger manufacturing companies have responded to the competitive pressures of globalization and the lack of an adequate domestic policy response by offshoring R&D as well as processing activities. This strategy has helped these firms but has also taken value added out of the US economy.

Smaller firms often do not have this option and are suffering to a greater degree from increasing foreign competition (Petrick 2009). A recent study by the American Small Manufacturers Coalition (ASMC) estimates that one-third of small manufacturers (90,000 firms with sales less than $10 million in annual revenue) are not at or near world-class in any element of corporate strategy. For larger firms (more than $100 million in revenue), a

[1] Source: Thomson Reuters' *Derwent World Patents Index*.

[2] These R&D intensities are for company-funded R&D. Adding externally supplied R&D funding (largely from the US government) increases the ratios slightly. For example, using "total R&D performed" as the metric raised the US manufacturing sector's R&D intensity in 2007 to 4.1%.

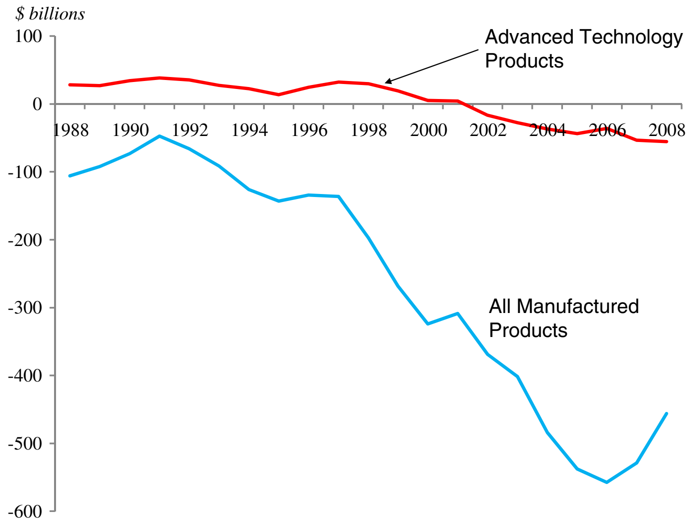

Fig. 1 US trade balances for high-tech and all manufactured products. *Source*: Census Bureau, Foreign Trade Division

smaller share (14%) are estimated to be equally deficient. Given that the US economy has 282,000 small and midsize manufacturing firms, this deficiency is a significant threat to overall US competitiveness.[3]

Moreover, the problems of this fraction of US manufacturing firms represent only a portion of the widespread competitive deficiencies affecting the entire sector. Figure 1 clearly shows the long-term process of decline even for the "high-tech" portion of the domestic manufacturing sector. The balance of trade for "advanced technology products" was in surplus from 1988 until 2002, when it turned negative.[4] This trend has continued, even in the face of approximately a 25% decline in the major-currency US dollar index during this decade.[5] The underlying problem is that US manufacturing firms are attempting to compete largely as independent entities against a growing number of national economies in Europe and Asia in which government, industry, and a broad infrastructure (technical, education, economic, and information) are evolving into increasingly effective technology-based ecosystems.

More specifically, such "national system" models of economic growth are increasingly attractive to global companies, as they enhance the productivity of private-sector R&D and increase access by companies to external sources of technical knowledge. Consequently, companies are allocating more of their global R&D budgets to countries that provide more efficient R&D infrastructures and greater financial incentives for the R&D itself. The

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[3] American Small Manufacturers Coalition, *Next Generation Manufacturing Study* (June 2009) http://www.smallmanufacturers.org/picts/NGM-Overview-and-Findings.pdf.

[4] The Census Bureau uses approximately 22,000 product codes to collect trade data. 500 of them are labeled as "advanced technology products" and a separate trade balance has been computed for this subgroup since 1988. The ATP balance was positive every year until 2002, when it turned negative. The deficit has grown every year since 2002 and provides one of several alarming indicators of the declining competitiveness of US manufacturing.

[5] Federal Reserve Board foreign exchange releases. In the period 2000–2008, the dollar declined 24.4% against an index of major foreign currencies (16.9% against all currencies).

impact of this trend is dramatically apparent in NSF survey data that show US manufacturing firms' investment in R&D outside the United States grew from 1999–2007 at almost three times the rate of these companies' domestically funded R&D.[6]

Yet, no comprehensive domestic manufacturing strategy exists. A major historical reason for the omission of manufacturing from economic growth policy initiatives is that most economists find no problem with the progressive shrinking of manufacturing's role in US economic growth. These neoclassical economists, who have dominated government policy advisory positions for decades, cite the law of comparative advantage as the rationale for being content with the ongoing global reallocations of manufacturing assets to other economies. Under this "law", resources are reallocated to wherever in the world they can be most efficiently used, which raises aggregate global economic welfare. Specialization is also argued to lead to higher real wages for the US economy through a virtually automatic adjustment mechanism that reallocates resources into new higher productivity areas of the domestic economy.

In fact, the US economy has been the innovator of virtually all major technologies in the post World-War-II era. Looking backward, neoclassical economists have been able to assert that domestic resources left idle by offshoring would automatically shift to new, higher productivity industries. And, they were right as long as the global technology-based economy could be accurately described largely by a one-country technology-based growth model. In such a model (no significant competition), no matter how inefficient and hence long are domestic innovation processes, resources impacted by offshoring are eventually reallocated to higher productivity sectors. Even when the global pace of technological change began to accelerate and thereby threatened to restructure comparative advantage against the United States, the domestic economy's installed base of technology-producing assets allowed it to extend its high-income position for a period of time.

Such experience leads to a strong "installed-wisdom effect," which is characterized by the inability of the leader to recognize the need for radical change in economic growth strategy in response to major changes in the global economy—in particular, changes in the nature and extent by which countries compete on the basis of technology (Schumpeter 1950; Christensen 1997; Tassey 2007a).

This effect derives in part from a related "installed-base effect," whereby the leading economy accumulates massive amounts of technological, physical, human, organizational, marketing and other assets during the process of reaching the position of economic leader. Consciously scrapping these assets that worked well in the past is a difficult decision to make and is typically deferred. In contrast, emerging economies, with no such installed base of assets and no ties to past "wisdoms," more readily adopt new asset structures and ways of competing.

The combined effect of a pluralistic technology-based global economy and the unwillingness of the domestic policies to force adaptation is that technological change cannot only shift comparative advantage through trade but lower real incomes in the economies that do not develop and use new technologies to a sufficient degree. Yet, only a few US economists, including Nobel Laureate Paul Samuelson, seem to understand this dynamic of long-term global competition. Referring to the role of technology, Samuelson states that "invention abroad that gives to [other countries] some of the comparative

[6] Sources: National Science Foundation's *Science and Engineering Indicators 2006* and *2008* and *Research & Development in Industry 2007*. Between 1999 and 2007, foreign R&D funded by US manufacturing firms grew 191% and their funded R&D performed domestically grew 67%.

advantage that had belonged to the United States can induce for the United States permanent lost per capita real income" (Samuelson 2004, p. 137).[7]

In contrast, with mainstream economists arguing that "fair free trade" more or less automatically benefits all trading partners through "negotiated" specialization, the media have picked up on this conventional wisdom, thereby reinforcing out-of-date economic doctrine. For example, in a May 25, 2009 editorial, the *Financial Times* recommended that Japan follow the US–UK strategy of largely giving up on manufacturing and thereby "support high-paying research and management jobs" in the domestic economy.

In summary, the installed wisdom effect has embodied a highly simplistic view of the role and impact of technology, to continue to dominate US economic growth policy. In contrast, a growing number of competing nations are adopting "innovation-economics" principles—an extension of "neo-Schumpeterian" economics (in reference to the famous Austrian economist Joseph Schumpeter). Schumpeter's best known concept is the process of "creative destruction," which describes how new technologies replace old ones and thereby create new competitive advantages within and across nations. A major implication of this body of thought is that relative incomes can and do shift across national economies in response to technological change.

The important policy implications of innovation economics, to be described in detail in the following sections, are (1) the potential exists for competing nations to create comparative advantage through technology and thereby shift relative prices and ultimately incomes in their favor, and (2) purely private-sector reallocations based on relative prices will result in a relentless decline in an economy's share of global income, as other economies with public–private technology investment strategies more rapidly and efficiently innovate and acquire dominant market shares.[8]

The economics of the innovation economy is complex and therefore so are the required economic growth policies. If nothing else, the remainder of this paper will demonstrate this fact. However, there is no getting around this complexity if successful national growth strategies are to be developed.

2 The economic rationale for high-tech manufacturing

Between 2007 and 2009, the US economy lost over 8 million jobs—the largest decline in any recession since the Great Depression. The unemployment rate exceeded 10% for only the second time since 1948. Particularly alarming is that approximately half of the unemployed have been permanently terminated. Analyses by economists, Wall Street analysts and others have been about when the severe cyclical distortions will subside, allowing employment to stop declining and eventually start growing again. This debate ignores the structural impediments in the US economy that will constrain domestic employment growth long after the recession is officially over.

The unemployment rate is known to be a lagging indicator of an economic rebound because companies use temporary workers and overtime until growth in demand is sufficiently established to rationalize hiring additional workers. In the meantime, companies pay existing workers overtime and invest in productivity enhancements. The problem going forward is that this lag will be far longer than anticipated and even when hiring

[7] See also Hira (2009).

[8] See Atkinson and Audretsch (2008) for a review of the differences between these two bodies of economic thought.

begins it will be tepid. Federal Reserve data show that capacity utilization in the manufacturing sector hit a record low in June 2009 of 65%. Due to some inventory rebuilding and short-term government stimuli aimed at specific industries, the utilization rate rose slightly to 68% in September, but it is still well below the average for the 1990s of more than 80%.

One reason for a predicted sluggish recovery is the huge overhang of household debt that will restrain consumer spending (households account for about 70% of GDP). It will take years to rebalance household finances. But, the even more important reason because of its long-term implications for domestic rates of economic growth is globalization. Dominated by the installed-wisdom and installed-base effects, the US economy has largely ignored the implications of global trends for decades, thereby allowing structural problems to accumulate. Such deficiencies take decades to build up and unfortunately take a long time to remedy. Thus, initiatives to support selected industries with short-term stimuli will do little more than create a temporary blip in the secular decline. Some of these industries have such inadequate overall competitive strategies and receive such little long-term support from government for restructuring that their demise is either substantially complete or will soon be so.

Most important, and unfortunately least understood, is the fact that the dynamics of changing comparative advantages among nations is not accurately explained by examining individual technologies and industries. Most modern technologies are systems, which means interdependencies exist among a set of industries that contribute advanced materials, various components, subsystems, manufacturing systems, and eventually service systems based on sets of manufactured hardware and software. The modern global economy is therefore constructed around supply chains, whose tiers (industries) interact in complex ways. In the US economy, one supply chain after another has been hollowed out by increasing foreign competition. Most of these losses have been in manufacturing. In spite of arguments to the contrary, partial domestic supply chains often have increasing trouble competing globally. This proposition is complex, varying among technologies and hence high-tech supply chain. However, it is a real phenomenon that is receiving little analysis.

More specifically, loss of competitiveness in a single tier within a supply chain is not an isolated event. The sources of technology in the modern economy and the interdependencies among technology-based industries explain why the United States needs a manufacturing sector and why this sector requires a substantial restructuring and expansion through investment in advanced technology. Specifically, a high-tech manufacturing sector is essential for the following reasons:

(1) Bureau of Labor Statistics data clearly show that high-tech workers in general are paid substantially more than workers in other occupations; therefore, the high-income economy must be the high-tech economy and this includes a competitive manufacturing sector, as it contains many of the most R&D-intensive industries.
(2) Manufacturing still contributes $1.6 trillion to GDP and employs 13 million workers. Allowing this sector to decline further requires strong guarantees that high-tech (i.e., equal or better paying) service jobs will appear to replace the lost manufacturing ones.
(3) The majority of trade is still in products; thus, for the foreseeable future, the US economy cannot remove the huge and persistent overall trade deficit by relying on services.

(4) One characteristic of traditional services has been the requirement for delivery directly to the consumer, which means importing such services is not feasible. However, the advent of the Internet and other IT-based technologies has made the high-tech and high-value-added service jobs much more "tradeable". This fact reduces the asserted superiority of services as a long-term, single-focus economic growth strategy.

(5) High-tech services are now being pursued vigorously as a domestic growth strategy by a growing number of countries. That is, the process of convergence, that has been underway in high-tech manufacturing for several decades, is now accelerating in high-tech services. Thus, the argument that the US economy can easily evolve into a pure service economy and also continue as the high-income economy ignores the long-term implications of this trend.

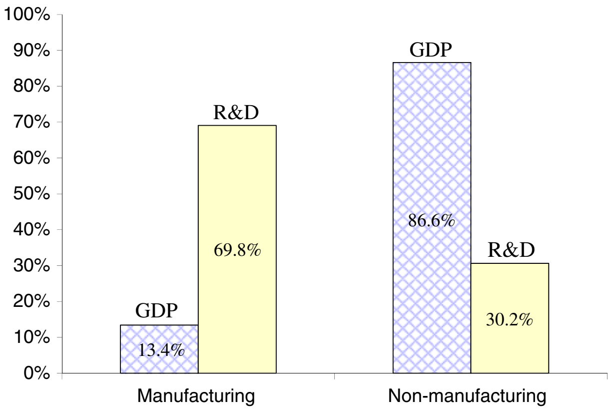
(6) The ability of the domestic economy to be competitive in high-tech services will continue to require close interactions with the creators and suppliers of technologically advanced hardware and software. Manufacturing R&D remains the dominant source of service-sector technologies, so service companies "import" much of their technology from this sector. The large percentage of industry R&D accounted for by manufacturing companies (70%) means that the demise of a substantial domestic high-tech manufacturing sector would greatly diminish the size and also the efficiency of the overall domestic innovation infrastructure. It would do so by reducing scale and scope economies in establishing and conducting R&D in universities, government labs, etc. In fact, manufacturing companies employ approximately the same relative share of scientists and engineers as their contribution to national R&D performance. Under a "service-sector-only" growth scenario, this skilled pool of researchers would be unavailable to the developers of high-tech services. The fact that more and more manufacturing companies are integrating forward into services underscores the existence of co-location synergies between these two sectors.

(7) Finally, economic studies have shown that because much of the knowledge underlying emerging technologies is tacit in nature (i.e., requires person-to-person contact for efficient transfer), co-location synergies are critical. Such synergies are accentuated by the fact that modern science-based industries are increasingly multidisciplinary and therefore require far greater and more complex interactions among a number of technology experts in different fields. This phenomenon could be argued to exist more strongly within individual industries between R&D and manufacturing, but the complexity of downstream integration activities means that it applies to interactions among manufacturing industries and between manufacturing and services, as well. Thus, hollowing out of domestic high-tech supply chains can have a negative effect on any one industry's growth potential.

3 Trends in US manufacturing

In assessing the current and longer-term investment imperative for the US economy and the potential for manufacturing to continue as a major contributor to national productivity growth, historical trends are instructive. In 1957, manufacturing accounted for 27% of GDP. 50 years later in 2007, it accounted for less than 12%. From 1965 to 2000, US manufacturing employment remained stable at around 17 million, while the value of shipments in constant dollars continued to grow as the direct result of productivity growth.

Fig. 2 Sector shares of industrial R&D performance and contributions to GDP, 2007. *Source*: Bureau of Economic Analysis, National Science Foundation



This growth resulted from US-based companies investing in automated process technologies while offshoring medium and low-technology production and importing these components at cheaper prices.

During the current decade, however, a pronounced decline in manufacturing employment has occurred, largely due to the rapidly increasing attractiveness of other economies as places to produce goods. In the 2000–2008 period, approximately 3.8 million domestic jobs were lost in this sector.[9] At the same time, the combined constant-dollar value of shipments of durable and nondurable goods has stopped growing, remaining basically unchanged through 2007.

An additional concern is the fact that manufacturing firms perform approximately 70% of industry R&D, as shown in Fig. 2. In 2007, manufacturing firms employed 63.4% of all domestic scientists and engineers (Wolfe 2009). Clearly, this sector is an essential component of the US technology-based economy and, in particular, an essential part of an export-led growth strategy.

Equally important, the innovative output of the manufacturing sector is the set of components that the dominant and increasingly high-tech service sector combines into the technological basis for the services in today's advanced economy. One need only note the ongoing shift from pure high-tech manufacturing to integrated manufacturing-service strategies to appreciate the critical importance of growth policies that focus on the entire high-tech supply chain. Doing so targets much larger potential value added and hence much larger employment and profits for the domestic economy.

In contrast, if domestic high-tech manufacturing is allowed to move offshore, the US lead in high-tech services will be increasingly threatened by economies that are creating co-location synergies between the developers of hardware and software and the high-tech services that integrate these components into the system that provides the service to customers.

Moreover, high-tech services are not the economic panacea that is often claimed for them. A growing number of other countries are including technology-based services in their long-term economic growth strategies. One study estimates that 30 economies have

[9] Congressional Budget Office, "Factors Underlying the Decline in Manufacturing Employment Since 2000" (December 23, 2008).

policies in place to promote service exports (Kennedy and Sharma 2009). This trend increases the imperative for a diversified and better integrated domestic economy.

Finally, service-sector R&D consists largely of systems integration, with hardware and software being imported from manufacturing industries (Gallaher et al. 2006). Innovative service design and hence competitive success can depend on adequate lead times with respect to advances in components of service systems. Thus, close interaction with suppliers is essential. Moreover, by virtue of being at the end of several technology supply chains, service industries are typically far removed from the majority of the scientific establishment, which further reduces their understanding of emerging technological trends. These facts mean increased dependence on hardware and software firms for information on technological opportunities and implications for strategic planning. Co-location enhances exchanges of such information.

This is not to say that such exchanges cannot occur over long distances, overcoming language and cultural barriers, currency swings, and differences in intellectual property laws. Modern IT infrastructures have greatly increased the efficiency of communication. However, for certain types of R&D, at least, the efficiency of doing so is significantly less relative to the increased speed of information transfers made possible by new efficient R&D infrastructures within the domestic economy that more closely integrate domestic supply chains. Other countries are making significant investment in such R&D infrastructures. Thus, the emphasis on global R&D networks, while important for the market strategies of global corporations, has negative implications for domestic economic growth policies for the simple reason that the offshoring of R&D takes valued added out of the domestic economy and this loss is frequently followed by further loss of value added from subsequent manufacturing that is co-located with the source of R&D.

In the end, relative effectiveness of technology investment and utilization strategies will determine national rankings in the global economy. With current annual global R&D expenditures of $1 trillion and many more R&D-capable economies, countries' efforts to "tilt the flat world" through newly created or newly absorbed technology is an increasingly frequent phenomenon. Nanoscience and nanotechnology research is a standout example, as global R&D in this area is evenly distributed among North America, Europe and Asia.

The forthcoming pattern of distributed sources of nanotechnology is the forerunner of a much more competitive global innovation economy. The higher rates of growth of new scientists and engineers in a number of countries compared to the United States along with faster rates of growth in R&D spending mean more of the higher paying technical jobs will be located outside the United States. Although most of the policy literature focuses on technology's impact on productivity and subsequently market shares, a less-noted consequence is that labor receives much higher wages on average in high-tech occupations. These workers earn from 50 to 100% more than the average for all workers (Hecker 2005). Thus, the global dispersion of high-tech jobs is a particularly serious trend for domestic economic growth policy.

An important metric of an economy's competitive position is its share of the global valued added produced by an industry or sector. The industries making up a supply chain all contribute valued added, which when summed up constitutes the value of "final demand" collectively met by this set of industries. Thus, the policy message is to devise and implement a supply-chain-wide growth strategy for manufacturing that captures large shares of the most lucrative markets for manufactured goods. Over time, these markets will be the technology-driven ones.

However, despite the massive offshoring of low-tech manufacturing over the past four decades, many of the remaining industries are still not sufficiently R&D intensive.

Table 1 Relationship between R&D intensity and output growth

Industry (NAICS code)	Average R&D intensity, 1999–2006	Percent change in real output, 2001–2006
R&D intensive		
Pharmaceuticals (3254)	10.3	38.3
Semiconductors (3344)	9.8	19.7
Medical equipment (3391)	8.1	39.2
Computers (3341)	6.3	83.9
Group Ave	8.6	46.6
Non-R&D intensive		
Machinery (333)	3.8	12.3
Electrical equipment (335)	2.5	-6.3
Plastics & rubber (326)	2.3	4.6
Fabricated metals (332)	1.4	7.8
Group Ave	2.5	4.6

Sources: NSF for R&D intensity and BLS for real output

Table 1 indicates the significant performance differences between R&D-intensive industries and those that are moderate-to-low R&D intensive in terms of real output. The data show the superior performance of technology-driven economic activity.[10]

This long-term growth imperative, requiring structural changes in the domestic economy, has been obscured by the current economic crisis and the need for massive cyclical stabilization efforts. The current US problems are the result of excessive consumption financed by an enormous accumulation of debt. This era is over. Debt accumulation can be rationalized—if it is used for investments in productivity-enhancing capacity and is limited in duration. However, in this decade (2000–2008) total credit market debt increased 99% while GDP grew by less than half that rate (45%). One of the major manifestations of this debt-driven growth was a national savings rate that hovered around zero for most of this decade. Approximately zero savings has meant that, in effect, virtually all investment has been financed by foreign capital. The huge debt burden will require years of low consumption, as American consumers refurbish their balance sheets. This means a drastically new growth strategy is imperative.

The dramatic shift that has finally begun in the US economy from a consumption-led growth strategy to one that will be productivity and export driven will require a renewed focus on saving and investment that yields long-term accumulation of productive assets, as this strategy is the only way to grow real incomes in the long run. Increasing productivity is especially compelling as the world's economy is currently confronted with a sharp downshift in demand. The consequence of global excess capacity is a combination of falling prices and reduction in less-productive capacity, which means that only the most efficient existing or created economic assets will be viable. To survive, companies, industries and entire economies will have to become more productive by rapidly assimilating existing technologies and developing new ones.

[10] Government data are not sufficiently disaggregated (in particular, to the industry level) to allow all desirable comparisons. For example, Machinery (NAICS code 333) is a large and diversified group of industries. Most of them are low- to moderate-R&D intensive. A few, however, such as semiconductor equipment (code 333295), are R&D intensive and produce high value-added products.

Table 2 Trends in value added by major industry group

Industry (NAICS code)	% Change in value added		R&D intensity 2003
	1985–2000	2000–2007	
GDP	132.6	40.6	2.6
Manufacturing (31-33)	(92.7)	(13.4)	3.6
Motor vehicles and parts (3361-63)	(84.0)	(−16.6)	(2.5)
Textiles, apparel and leather (313-16)	(8.2)	(−30.4)	(1.6)
Computer & electronic products (334)	144.5	(−21.2)	9.0
Publishing, including software (511)	225.1	(18.9)	17.1
Information & data processing (518)	305.4	63.7	8.7
Professional, scientific & Tech. services (54)	249.6	49.3	10.0
Health care (621-23)	194.6	60.4	3.9

Source: Bureau of Economic Analysis for value added and National Science Foundation for R&D intensity

The rapid assimilation of new technologies in response to an economic crisis is the classic Schumpeterian creative destruction model in which these technologies often penetrate markets slowly or even lie latent in various phases of development until a crisis erupts that changes relative prices, thereby creating demand for productivity-enhancing assets. In fact, previous severe economic crises (such as the 1930s and 1980s) were characterized by an acceleration of technology assimilation, as companies tried to cope with shrinking demand by increasing productivity (Bhidé 2008).[11]

While this pattern is unfolding to some degree in the current recession, the drag of consumer debt repayment and the zero growth in real household income since 1998 are restraining savings and thereby inhibiting investment by both the private and public sectors. Most important, even when the current global contraction passes, the increasingly intense competition among nations will continue to intensify, as described in the following section.

4 The shifting of global competitive positions

The incremental, uneven, and hence insidious decline in overall competitiveness of the US manufacturing sector is indicated in Table 2 by recent trends in value added (contributions to GDP) for a number of major industry groups. The trends are divided into two time periods. The first period, 1985–2000, approximates the beginning of intense foreign competition for technology-based product markets. The bottom-line impact was increased offshoring and domestic investment in information and other productivity enhancing technologies to combat the combination of growing global technology competence and lower labor costs. The second time period is the current decade (data available through 2007) in which offshoring has accelerated and broadened its impact on the US economy.

[11] Bhidé points out that the 1930s had the highest productivity growth of any decade in the twentieth century. Technologies developed in the 1920s but not widely adopted then were rapidly diffused in the 1930s in response to corporate desperation to remain viable in the face of falling demand. Similarly, the severe recession of the early 1980s and the onset of significant foreign competition led to rapid diffusion of the PC and other information technologies, as well as concerted efforts to revitalize high-tech industries, in particular, semiconductors.

The growth rates in parentheses in Table 2 identify industry groups that underperformed the economy as a whole in that time period (as indicated by GDP growth). From 1985 to 2000, manufacturing's contribution to national value added grew somewhat slower than overall GDP (93 vs. 133%). Within manufacturing, some traditional industries, such as those making up the automotive supply chain (84%), grew more slowly than the sector as a whole. Low-R&D intensity industries grew much slower, as they were the early victims of globalization. For example, the value added by textiles, apparel, and leather goods barely grew at all during this period (8%). In contrast, the four service industry groups shown (three of which are highly R&D intensive) significantly outperformed the broader economy with growth rates in the 200–300% range.[12]

The column in Table 2 for the current decade indicates that the situation has deteriorated significantly. The continual encroachment of foreign competition has led to a dramatic decline in the growth of value added in manufacturing. In the 2000–2007 period, manufacturing's growth rate has fallen substantially relative to overall economic growth (to 33% of the economy's growth rate vs. 91% of GDP growth in the prior period). The value added by the automotive supply chain and textiles, apparel, and leather actually declined 17 and 30%, respectively. That is, traditional (low to moderate R&D-intensive) industries have not only underperformed relative to the economy but have actually shrunk (negative growth for value added).

The supply chain is the key unit of analysis for understanding the interdependencies of related industries and hence the potential for broad erosion of domestic valued added. When domestic consumer-product manufacturers lose market shares, the domestic supplier industries that support them tend to contract as well. The increasingly sophisticated machine tool industry, which is essential to all discrete parts manufacturing industries, has dramatically declined in the United States. Once one of the world's leaders, US sales now account for less than 5% of global output. Not surprisingly, with US parts manufacturing declining, domestic consumption of machine tools dropped 30% over the most recent decade for which data are available (1998–2007) and machine-tool producers moved offshore or lost markets to competitors in other economies where parts manufacturing was expanding.[13]

This phenomenon is due in part to co-location synergies, which are more pronounced the more R&D intensive the supply chain. The important point is that the traditional OEM-led supply chain where the OEM conducted the majority of R&D and controlled component design is rapidly being replaced by a more efficient "value-stream" supply chain in which R&D is significantly distributed (Petrick 2009). This evolutionary trend is the result of the increasing pace and complexity of technological change. The value-stream supply chain requires much more collaboration among the supply chain's tiers. Such intense product development iterations between customers and their suppliers benefit from co-location. Boeing's move to a value-stream supply chain strategy in which suppliers are located in many different countries created coordination problems that seem to be largely responsible for the 2-year delay in flight testing the 787 Dreamliner (Petrick 2009).

Further, within a single tier in a high-tech supply chain, "design for manufacturing" is an important productivity factor. Separating the two activities (R&D and processing) inhibits the exchanges of tacit knowledge (through person-to-person contacts) that greatly shorten time to market and subsequent improvement of the critical performance-cost ratio.

[12] R&D intensity is conventionally defined as R&D divided by GDP for the entire economy and R&D divided by sales for companies, industries, and sectors.

[13] See McCormack (2009) for this and other examples of declining US manufacturing industries.

However, the loss of co-location synergies from globalization varies across industries, which complicates growth policy analysis. For some industries, especially those with relatively mature technologies, the advent of elaborate IT infrastructures enables much more efficient communication over distances among tiers in the relevant supply chain. Still, such synergies exist and are especially important for emerging technologies, which are increasingly targeted by national innovation system strategies that promote R&D efficiency (through support for technology clusters and supporting technology infrastructures) among tiers in the emerging supply chain.

The impact of this latter phenomenon is indicated in Table 2 by the dramatic drop in growth for several R&D-intensive industry groups. These are the industries that the neoclassical economists argue will automatically fill the gaps in employment and income resulting from the offshoring of traditional industries. The manufacturing group, computer and electronic products, has dropped from a position of above-average performance in 1985–2000 (144% growth in value added) to a 21% decline in the current decade. This trend is clearly the result of the steady offshoring of products from the multiple industries in this group. For example, the size of the domestic printed circuit board industry, which supplies components used in "tens of thousands of different products," shrunk from $11 billion to $4 billion during this decade (McCormack 2009). The Chinese have become the world's largest exporter of IT equipment and many of the components making up these products come from other Asian economies.

A major tenet of this strategy is the promotion of co-location synergies. The printed circuit board industry was once relatively labor intensive, which led to its offshoring. Today, its production process is highly automated (low unit labor content), but other countries have automated, as well, and the majority of the global industry remains in Asia near the next tier in the electronics supply chain (assembly). Taiwan has a strategy based on the national innovation system concept to become an integrated semiconductor device manufacturer. Moreover, it is integrating further forward into higher valued-added electronic products, just as Japan did in the 1980s.

Again, one can attempt to deny the importance of such trends by pointing out, for example, that the majority of Chinese "chip design" is currently not state of the art and hence cannot compete with US companies. However, China has the same objective as Taiwan and Korea, which is to steadily integrate backward from assembly and testing to wafer fabrication to design and eventually to consumer products. While it makes a difference from a business model perspective whether these activities are separate tiers in a global supply chain (different companies at each tier) or are all done by integrated device manufacturers within single economies, the economic effect is the same: loss of value added within the US domestic supply chain.

Thus, although the US-based companies still have the largest share of global semiconductor sales, their market share is being steadily eroded by foreign competition. Most important for domestic economic growth, the US domestic shares of semiconductor-device production capacity and sales have declined in this decade and the domestic industry is no longer a player in a number of areas of semiconductor equipment, such as lithography. Farther back in the supply chain, critical materials and wafer production are now largely performed in other economies.[14]

[14] Source: Semiconductor Industry Association (SIA). Ironically, a National Research Council Report (*Securing the Future*, 2001) pointed out that the US electronics industry in 2001—the beginning of the second time period in Table 2—was the largest US manufacturing industry in terms of sales and that the US

As traditional hardware and software are increasingly integrated, the potential for co-location synergies exists between the two categories of assets, as well. Table 2 implies that software has also undergone a huge decline in domestic value added between the two periods. However, BEA data do not allow separation of value added from software and traditional publishing (which has shrunk in recent years due to the advent of the Internet as an increasingly important source of information). Even so, the high R&D intensity for the entire industry group indicates that software accounts for a major share of this group's economic activity, so a significant portion of the decline is likely due to offshoring of software development, production, and services.

In summary, the policy imperative is to understand the importance of co-location synergies as part of a growth strategy that maximizes domestic value added, as this metric is the bottom line for economic growth policy. And, because value added is mainly payments to owners of capital (profits) and payments to owners of labor (wages and salaries), the policy analyst must also understand the factors affecting the distribution of valued added between the two classes of economic agents.

5 The causes of declining competitiveness

The key point for economic growth policy is the fact that it is not the US semiconductor companies or other R&D-intensive firms that are in trouble. US-based companies are still expanding R&D and manufacturing capacity. As a group, they remain the overall leaders in technology development.

Rather, it is the US economy that has the problem because increasing proportions of new corporate investment are in other economies. A Semiconductor Industry Association (SIA) survey of R&D and capital spending by US semiconductor companies for the decade 1997–2007 found that spending on domestic R&D by these companies increased in absolute terms (54%), indicating a continuing significant commitment to domestic technology development. Investment in wafer fabrication capacity grew more slowly (10.6%), and investment in assembly and testing declined (−21.4%). Most important are comparisons of domestic and foreign investment trends: domestic shares of total company spending declined in all three major categories: R&D, wafer fabrication, and assembly & testing (Dewey and LeBoeuf LLP 2009).

The differential rates of offshoring across industries explain to a degree why policy-makers have had trouble understanding the seriousness of the aggregate long-term decline in US domestic competitiveness. While some categories of domestic spending decline, others continue to grow albeit at slower rates. However, the fact that all categories of investment outside the domestic economy are increasing even faster should be a loud and clear warning that major policy shifts are needed. The SIA survey indicates that US semiconductor companies plan to continue offshoring R&D at faster pace than the growth in domestic spending over the next 5 years. The global scope of this offshoring and the roles of foreign governments in this process should not be minimized. For example, Singapore with a population of only 4 million has nevertheless attracted five state-of-the-art 300 mm wafer fabs and US company R&D spending in Europe is projected to double in the next 5 years (Dewey and LeBoeuf LLP 2009).

Footnote 14 continued
semiconductor industry (a portion of the electronics industry group) had the highest value added in 1999 of any US manufacturing industry.

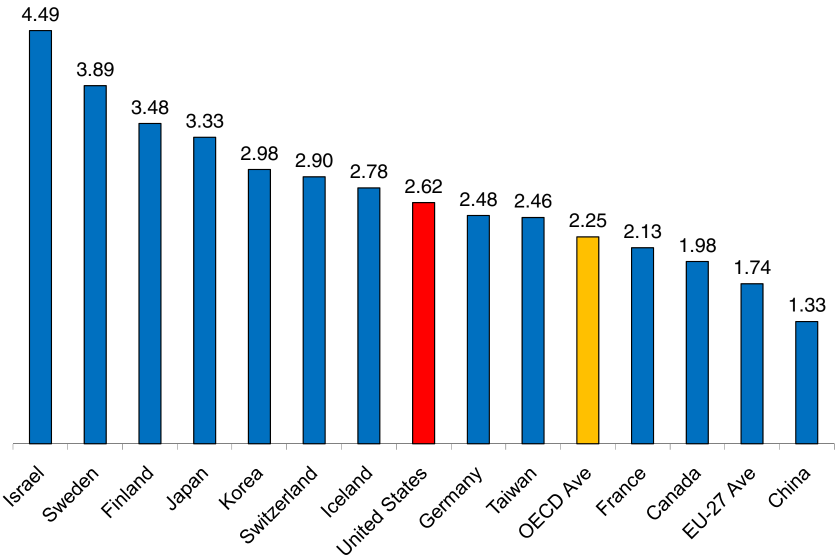


Fig. 3 National R&D intensities, 2005 (gross R&D expenditures as a percentage of GDP). *Source*: OECD, Main Science and Technology Indicators, May 2007

The major policy lesson is that the creation of a "national innovation system" (the organized collection of public and private assets that create and utilize technologies) takes a long time and considerable resources to develop. Over the past 10 years, most offshored semiconductor R&D has been to Europe because R&D infrastructure support is more fully developed there than in the emerging economies of Asia. That is changing, as Asian nations are making large and continual investments in such infrastructure.

It is also the case that the erosion of a national innovation system takes a long time because (1) public and private investments continue, just at a lower rate relative to the rest of the global economy, and (2) competing economies have the same challenges in accumulating innovation assets. Thus, while competitiveness rankings across countries still show the US economy highly placed, the trends are negative. With respect to innovation-based competitiveness, a recent benchmarking of US and European nations against the world by the Information Technology and Innovation Foundation (ITIF) ranked the US economy sixth. However, in terms of trend (improvements in innovative capacity), the United States was ranked last out of 40 economies assessed.[15]

Leaving aside the critically important issue of a national innovation infrastructure for a moment, the current trends in US R&D investment alone imply future difficulties in maintaining competitive positions in either the manufacturing or service sectors. One major indicator is the gradual but steady decline in US R&D intensity relative to the rest of the world. As indicated in Fig. 3, the United States, once the most R&D-intensive economy, has steadily slid to a current eighth position. Many economies are increasing their R&D relative to GDP, while the United States has the same R&D intensity as in 1960. Without major changes, US competitiveness can be expected to deteriorate further.

[15] See http://www.itif.org/index.php?id=226.

Even more important, only small fractions of both manufacturing and services are truly R&D intensive (R&D-to-sales ratios greater than 5%). These high-tech industries collectively account for only about 7% of GDP. The remaining 93% consists of moderate-to-low R&D-intensive industries, which are losing market shares and domestic employment at more rapid rates.[16]

One of the excuses for declining US competitiveness is the alleged higher compensation paid to US workers. While compensation rates in industrialized nations are higher than in emerging technology-based economies, total compensation per hour for US production workers is lower than in a large number of other industrialized countries. Yet, trade deficits, even in technology-based products, persist. BLS data show that in 2007 total compensation for US production workers was $24.59 per hour. This rate was lower than those for 16 other countries and lower than the average for Europe. In contrast, the US rate is 25% above the average for Japan and is 2.5 times higher than the average for East Asia ex-Japan.[17] These data indicate that US manufacturing at least has a competitive compensation structure among industrialized nations, so one would expect a better trade performance for the high-tech portion of manufactured products.

Another frequently cited excuse is the fact that the US dollar has been overvalued for some time and continues to be so, in spite of a significant decline in the current decade. A major reason for the slow adjustment of the dollar in response to a secular decline in competitiveness is its status as the world's reserve currency. However, as the history of the English pound in the last century demonstrates, all currencies eventually adjust to economic realities and no economy has ever prospered from a depreciating currency.

In addition, many analysts cite exchange rate manipulation by the Chinese as a significant factor in the failure of the dollar to completely adjust to economic realities. While justified, these complaints overlook the mechanism by which China "manipulates" the bilateral exchange rate. They do it by purchasing hundreds of billions of dollars of US Treasury debt. Doing so creates a substantial demand for dollars, thereby keeping the price of the dollar relative to the yuan above its true "economic" level. This is not a good long-term situation for either economy (the United States will continue to incur larger trade deficits and China will remain excessively dependent on exports). However, it persists and therefore remains a negative for US growth. Over time, this mutual dependency will dissipate because the Chinese will pursue other markets for their exports coupled with increased domestic consumption. As this process unfolds, the Chinese will greatly reduce purchases of US debt. Thus, the adjustment will be more difficult for the US economy, as it cannot increase domestic consumption without significant productivity growth. The alternative of growing exports through currency depreciation is not a long-term option.

[16] Author's estimate. No consensus definition of the "high-tech sector" exists. It is defined here as including 4-digit NAICS industries that have an R&D intensity (R&D divided by net sales) greater than 5%. Unfortunately, the Bureau of Economic Analysis does not calculate value added at the 4-digit industry level (they do so only for 3-digit industry groups and above). Thus, only a rough estimate can be made. However, even if the value added were used for the 3-digit groups in which these R&D-intensive industries are classified (a significant overestimate because these groups contain low and moderate R&D-intensive industries), the total contribution to GDP would still only be 12.5%.

[17] Bureau of Labor Statistics, "Production Workers: Hourly compensation costs in US dollars in manufacturing, 34 countries or areas and selected economic groups, 1973–2007," March 2009. (ftp://ftp.bls.gov/pub/special.requests/ForeignLabor/ichccpwsuppt02.txt.

While acknowledging the above diversified set of factors, the long-term problem for the US economy is structural and the solution therefore requires structural change. In addition to barriers associated with inadequate R&D spending and innovation infrastructure, a more subtle but reinforcing negative aspect of offshoring in individual industries is the previously described hollowing out of formerly integrated supply chains.

A confusing element of this phenomenon is the natural tendency of high-tech supply chains to experience vertical disintegration over time. Technologies emerge and mature through an evolutionary process in which integrated manufacturers dominate the supply chain for a period of time until the interfaces between components are firmly established and the markets become large. Standardized interfaces and economies of scale allow innovative specialists in individual components to enter the industry. The tier in a supply chain at which this vertical disintegration occurs has been labeled the "decoupling point" (Christensen et al. 2004b). The decoupling point tends to move backward in the supply chain over time from the final product to subsystems and then to component tiers. This phenomenon opens up competitive opportunities for many economies to compete at specific tiers high-tech supply chains.

The process is facilitated by ever improving information and computer technology (ICT) and the decreasing weight of many high-tech products, so that distributed global networks of value added are increasingly common (Atkinson 2009). R&D networks spread risk and combine complementary research assets through a process called "open innovation" (Chesbrough 2004). Such networks, using advanced IT infrastructure, are fast becoming an integral part of global supply chains and can often function quite well.

However, to the extent tiers in a supply chain are offshored, domestic research and other supporting infrastructures are degraded, which can be a major problem for the domestic industry in transitioning to the next life cycle. And, of course, the domestic economy loses the value added from offshored economic activity in the current life cycle.

Longer term, it is this evolutionary process in which domestic supply chains are (1) allowed to be hollowed out through the absence of aggressive policies to maintain value added throughout the current technology life cycle and then (2) not upgraded/replaced with new technologies as the current ones become obsolete that explains why aggressive emerging economies tend to "converge" with (grow faster than) established ones. This process of convergence has been well documented over the last several centuries encompassing two industrial revolutions, as technology became an increasingly significant factor in international competition. In the last four decades of the twentieth century, convergence accelerated significantly with a number of emerging economies doubling national income in 10–20 years compared with the 30–70 years required to double in the nineteenth century (Lucas 2009).

Most notable from this research are the findings that (1) the inverse relationship between per capita income growth and maturity only applies to open emerging economies, i.e., those economies that trade relatively freely with the rest of the world (closed emerging economies grew significantly slower), and (2) the increased rate of convergence is largely due to technology spillovers across national economies.

However, no theoretical construct exists that says leading economies cannot combat convergence and thereby maintain their high rankings in per capita income. One of the best targets for reversing the current trend in convergence by an increasing number of emerging economies relative to the US economy is manufacturing, as products still dominate trade and flows of technology. Doing so, however, will require considerably more aggressive growth strategies based on more accurate models of technology-based growth.

6 The economic growth policy problem

The central failure of current economic growth models is the assumption that shifts in relative prices will automatically elicit a Schumpeterian-type efficient reaction from domestic private markets—namely an adjustment involving development/assimilation of new technologies to replace offshored ones. Such an adjustment would enable a reallocation of resources from the offshored industry or sector to new ones that can provide both replacement and (historically) higher paying jobs.

This view of the adjustment process is based on past technological dominance by the United States, which economists and policy analysts have simply extrapolated to the present highly competitive global economy. This "installed wisdom" leads to the assumption that current rates of investment in R&D are adequate based on past trends. Further, the steady increase in industry's share of national R&D has been viewed as a good trend by many analysts because the innovation system is assumed to be synonymous with the actual act of innovation and therefore largely a private-sector activity. The result has been suboptimal aggregate R&D investment, but even more so, suboptimal R&D portfolios (type of R&D and diversification across technologies). In fact, the entire science, technology, innovation, and diffusion (STID) system is deficient, not only with respect to R&D strategies but also the quality of the S&T labor force and technology diffusion channels.

The neoclassical model that assumes new technologies will magically appear from advances in basic science and then drive reallocations of labor and capital into higher-tech, higher-productivity industries is now facing two increasingly severe obstacles. One is the relatively small high-tech sector. The other obstacle is a global system increasingly absorbing the output of US-based corporate R&D that in previous economic growth cycles would have stayed primarily in the domestic economy. That is, whereas in the past technology would flow from the new, domestic R&D-intensive industries into the remainder of the economy, thereby boosting overall national productivity, today such emerging technologies are flowing at least as rapidly to the innovators' foreign affiliates or foreign partners, in large part because the public sectors in other economies are facilitating the adoption of new technologies.

Convergence in current technology life cycles with subsequent loss of domestic market shares in the "first-mover" (innovating) economy begins when offshoring is initially undertaken in the form of relocating the production of low and moderate technology-based products to be near new markets and to achieve labor cost savings. The cost savings allow re-importation of these components by the original innovator, which lowers domestic costs and thereby helps raise the productivity of the remaining domestic production. Such strategies yield larger profits and help explain why US-based high-tech corporations had on average good balance sheets entering the recent severe recession (unlike government or the consumer) and why "measured" labor productivity has increased above rates observed in previous recessions.

While this situation bodes well for corporate investment in technology in the years ahead, such investment will increasingly take place in economies other than the United States. The loser in this process of global convergence is the American worker whose skill levels are increasingly matched or exceeded by ever larger numbers of foreign workers. Figure 4 shows the effect of these trends on the distribution of national income. Beginning in the 1980s, the push by American companies to adopt global strategies and the growing technological content of imports increased their productivity. Because much of the productivity growth was the result of offshoring, domestic labor benefited relatively little. This

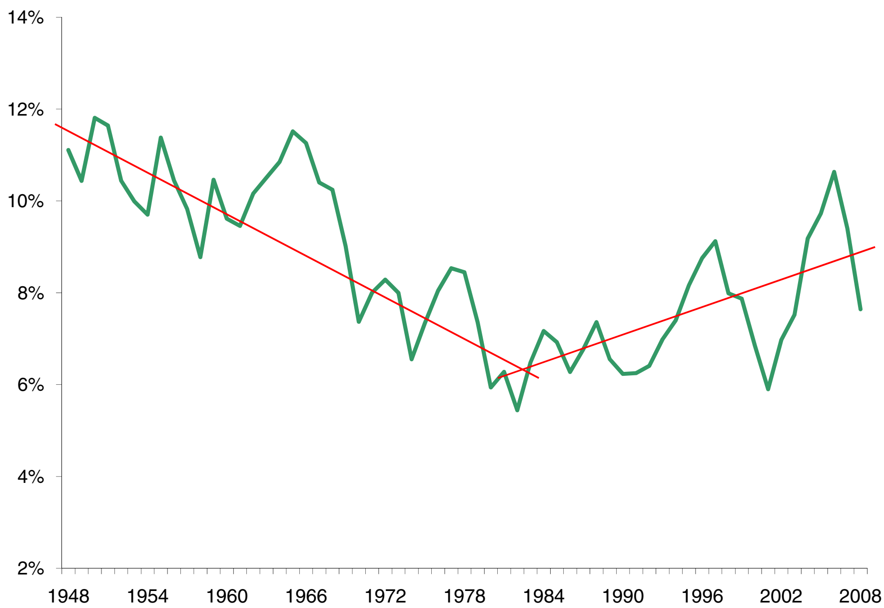


Fig. 4 Corporate profits (before taxes) share of GDP, 1948–2008. *Source*: Bureau of Economic Analysis, NIPA Table 1.14 for corporate profits before taxes (Gross Value Added). Domestic profits exclude receipts by all US corporations and persons of dividends from foreign corporations, US corporations' share of reinvested earnings of their incorporated foreign affiliates, and earnings of unincorporated foreign affiliates net of corresponding payments

trend became pronounced in this decade (2000–2008), as evidenced by the fact that inflation-adjusted US median household income dropped 4.2%.

In summary, the shifting of technology resource endowments among the world's economies can increase global economic welfare due to the advantages from specialization. However, in the ensuing redistribution of wealth, some economies gain more than others. That is, adjustments in accordance with the law of comparative advantage do not guarantee that all nations benefit equally—or benefit at all.

As is often the case with the dominant economy, the United States has not fully recognized the severity of the loss of competitive position. Helping mask the seriousness of this decline are (1) re-importation of cheaper components that have been offshored, which temporarily accelerates corporate productivity and thereby sustains output growth in the remaining domestic high-tech industries, and (2) the fact that offshoring (loss of market share) occurs at different rates among tiers in the relevant high-tech supply chain and thereby temporarily obscures the cumulative negative impact on domestic competitiveness and employment. The latter impact is finally becoming painfully evident, as US employment has had zero growth in this decade.

Thus, when earlier tiers in the electronics supply chain, such as semiconductor devices and printed circuit boards, are offshored and these components are imported at lower prices, the remaining downstream domestic industries realize a measured increase in productivity. However, the employment effect is negative. Only if the domestic industries using these components turn the cost savings into much higher sales can the net employment effect be positive.

Unfortunately, in an increasingly competitive high-tech global economy, downstream domestic systems companies (assemblers of components) not only outsource components all over the world, but they are also competing for market share with foreign systems firms that increasingly have the advantage of co-location with the offshored component suppliers. Only a few industries (such as US automobile OEMs) still reject open innovation strategies (Petrick 2009; Mann 2009). However, even where domestic industries have adapted, global open innovation means globally distributed value added. The result is constant restructuring of comparative advantage across national economies and hence shifts in relative rates of economic growth. Thus, open innovation, while a necessity for survival in most high-tech industries, is not sufficient as a long-term national growth strategy.

7 The economic losses add up

The aggregate loss of domestic market share for an entire supply chain is obviously much greater than for a single tier (industry). The cessation of growth in manufacturing output within the US economy in this decade reflects the effects of global convergence on many tiers in multiple supply chains. The bottom line is that the competitiveness of US manufacturing has eroded and this decline has been underway for decades. Thus, the end of the cyclical downturn in the global economy will not remove the structural problems responsible for this secular decline.

The most serious long-term implication is that without major shifts in US growth strategies, market shares from current technologies will not only continue to decline in the years ahead, but the substantial shrinkage will erode the supporting innovation infrastructure (universities and government laboratories, the supply of domestic skilled labor, venture capital infrastructure, etc.) needed to be competitive in future technology life cycles.

The main indicator of this long-term threat to the future of US manufacturing is the fact that higher-tech products are increasingly being produced overseas, as evidenced by the negative high-tech trade balance (Fig. 1). This deficit appears to be largely due to the trade imbalance with China. However, while striving to integrate backward in high-tech supply chains, China is still largely an assembler of high-tech components produced in other Asian economies. It is therefore the port of exit for the entire region, so the trade deficit represents a more pervasive problem. More generally, the US world-market share of exports by high-technology industries declined from about 20% in the early 1990s to 12% in 2005. The drop is primarily because of losses in export share by US industries producing communications equipment and office machinery and computers (National Science Board 2008). The loss of export markets is reflected in the drop in domestic value added for Computers and Electronic Products shown in Table 2.

In the face of offshoring, the law of comparative advantage can result in continued job and wage growth only if the lack of such growth in the shrinking economic sectors is compensated by growth in demand for high-skilled and hence high-paid labor in new industries. Conventional economic thinking, as evidenced by a recent CBO report, points to the continued growth in aggregate employment, even as jobs in manufacturing leveled off and then began to decline (Congressional Budget Office 2008). In the middle of the last decade (2004–2007), the US economy created about 7.5 million net new jobs. However, this job growth was driven largely by excessive consumption fueled by unsustainable

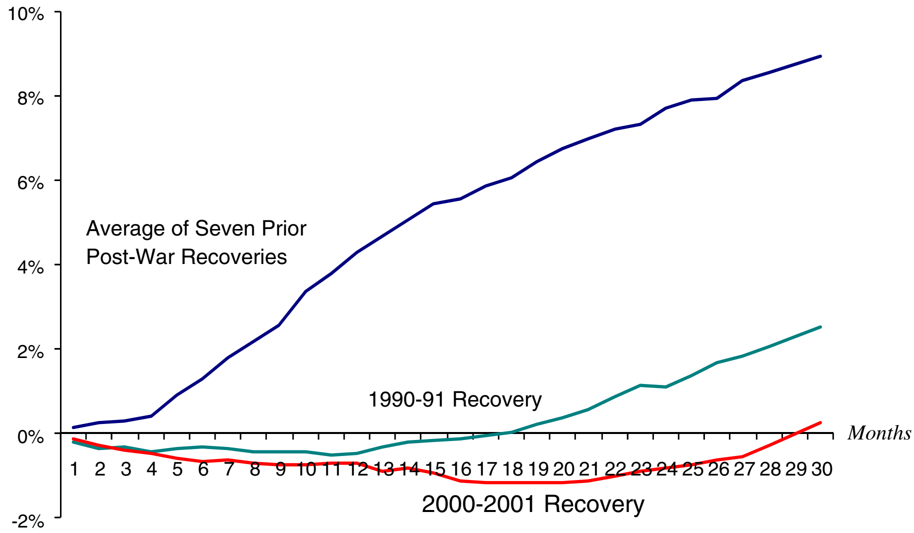


Fig. 5 Employment growth in post-world-war-II business recoveries: percent change from recession trough. *Source*: Tassey, 2007a (BLS for employment data; NBER for recession trough dates; employment data are for non-farm, private industry)

expansion of consumer and government debt. When the debt bubble collapsed, employment growth disappeared and, in fact, turned negative.[18]

The growing difficulty of increasing jobs of any type in today's increasingly competitive global economy is shown dramatically in Fig. 5. For the first seven recessions after World War II, the relatively closed status of the US economy meant that average employment recovery was swift and substantial (about 4 months to positive employment levels relative to the recession trough). In the late 1980s, however, the growing global competition began to promote greater investment in automation in addition to accelerated outsourcing. The result was that 19 months elapsed before a positive employment level was attained. This significant slowing of the cyclical rebound in employment was dwarfed by the extremely slow recovery in employment from the 2000–2001 recession, which required 30 months to reach a positive employment level relative to the recession trough.

8 The policy problem

Once the premise is accepted that the only way to achieve long-term growth in jobs for a high-income economy such as the United States is through investment in technology, innovation, and subsequent productivity increases, the key policy issue becomes how to promote desired long-term investment in a domestic economy that must save more and consume less, while reducing budget deficits through decreased spending and increased

[18] From the BLS establishment survey (http://www.bls.gov/schedule/archives/empsit_nr.htm#2000), non farm employment was unchanged in this decade (130.3 million in January 2000 compared to 130.8 million in October 2009). Employment in the manufacturing sector declined in the same time interval from 18.4 million to 11.7 million.

taxes. Economic text books state that in a closed economy national savings equals national investment. For a good part of the last decade, the national savings rate was close to zero. Thus, from a national accounting perspective, virtually all investment in this period of time was in effect funded through borrowed foreign capital.

Even with a return to modest domestic savings rates, the decision will have to be made to increase investment in R&D against competing demands for available funds. Further, R&D investment is only the first plank in a multi-faceted technology-based economic growth strategy. If economic growth policies focus only on developing new technologies, temporary monopoly profits will accrue to the innovator. Such profits have been used by many, including venture capitalists, to justify this focused investment strategy. However, from a national economic growth perspective, such a strategy ignores the need to remain competitive over the entire technology life cycle. In the middle and later phases of the typical cycle, the markets for the technology become much larger as secondary and tertiary groups of consumers adopt a widening variety of applications of the generic technology. However, much of the resulting greater value added accrues to imitators of the original innovation and these imitators (who also improve the original innovations) are increasingly in other economies.

Thus, as technologies mature and foreign competitors enter these markets, the domestic industry can lose value added, even relatively early in the life cycle. Such a scenario becomes more likely as more economies become technology based. In the current final phase of globalization of the technology-based economy, many nations are becoming innovators themselves, thereby shortening windows of opportunity for achieving innovation and ultimately target rates of return on investment (RoI) over the entire technology life cycle. Collectively, these trends have made the act of innovation more costly and risky.[19]

Total technology life-cycle policies must include broad education upgrades, dynamic technology portfolio management, and evolutionary technology infrastructure that adapts to industry's needs for competing in larger and more diversified markets. Strategies for managing the entire technology life cycle require both more accurate conceptualizations of industrial technologies and a better understanding of dynamics of technology-based competition.

9 Revitalizing advanced manufacturing policy: the multi-element technology growth model

Four general characteristics of modern manufacturing technologies serve as a basis for explaining why a new technology-based growth model is required for this sector:

(1) The typical industrial technology is a complex system of component technologies.
(2) These components arise from *generic technology platforms* and depend on commonly used *infratechnologies* (often in the form of industry standards); both of these elements are quasi-public goods and therefore require government support.

[19] A 2003 Boston Consulting Group study, *Innovation to Cash*, estimated that the cost of taking new products to market doubled over the previous 10 years and the innovation failure rate appeared to be in the 60–85% range. Christensen (1997) estimated the failure rate to be 80–90%. A more recent study by the Boston Consulting Group (*Innovation 2009*) found significant dissatisfaction with innovation RoI among corporate managers globally. Dissatisfaction was particularly high among North American companies (58%).

(3) Private-sector technology-based competition is driven by "draws" against these two technology elements (i.e., attempted innovations), so that an effective national innovation system must not only promote efficient R&D processes but also the efficient diffusion and assimilation of new technologies.
(4) System-level productivity must become the focus of economic growth policy, which means the supply chain (materials, components, equipment, systems, services) must become the focus of policy management, in contrast to the traditional emphasis on single technologies/industries.

The absence of the correct economic model to manage government support of advanced manufacturing continues to leverage the decline of this sector. A new government role will require both larger R&D spending and new and more efficient mechanisms for R&D funding and technology diffusion. The policy mechanisms to achieve this major revival of US manufacturing are not in place. Yet, the complexities of modern product and process technologies and their associated global markets create significant investment barriers for individual firms, especially small ones that require new, if not larger, government responses.[20]

Manufacturing is a particularly tough challenge because it is a complex systems technology that therefore requires innovation (1) at both the component and the systems levels, and (2) for both product and process technologies. Advances further require increasing integration of hardware and software technologies at both levels. An effective national R&D program therefore will need a complex research network and a significant supporting technical infrastructure.

The United States is the last major industrialized nation to accept the fact that industrial technologies are not black boxes (in economic terms, they are not pure private goods). In the traditional "black-box" model, science is a pure public good and is funded by government, while technology is a pure private good and is therefore funded by industry. Reality is that the typical industrial technology consists of three major elements that are distinguished by distinctly different investment incentives.

These different incentives result from the fact that the three technology elements have different degrees of public-good content (hence, the public–private nature of modern technology-based economies). Public-good content implies common use, which can be good and, in fact, essential for economy-wide growth. However, this sharing frequently occurs without adequate compensation to the developers. The public-good content of certain elements of technology-based economic activity is indicated in Fig. 6 by the shaded areas. The arrows show the direction of impact of one element or activity on others and hence indicate the potential targets of alternative policy instruments.

One of the three technology elements, proprietary technology, is the black box, i.e., the set of innovations. It is a pure private good and therefore is the province of the private sector. However, innovations (first commercial applications) cannot be efficiently derived directly from the underlying science base, which is a pure public good and hence is provided almost entirely by government funding.

Instead, scientific knowledge is used to develop "proofs of concept" that become the technology platforms (generic technologies) for subsequent innovative efforts. Such innovation-enabling platforms are technically "quasi-public" goods, in that their

[20] See van Opstal (2009) for an excellent characterization of the increasing speed and complexity of technological change.

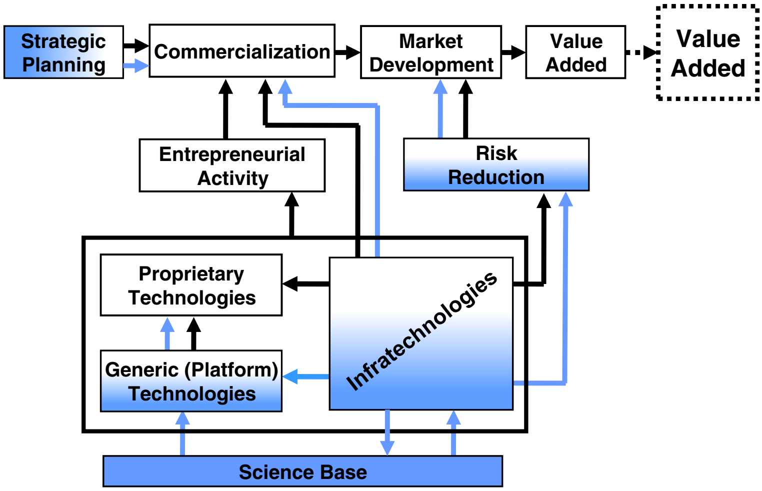


Fig. 6 Technology-element model. *Source*: Tassey (2007a)

development is particularly risky and they generate significant spillovers. They are therefore co-supplied by industry and government (Tassey 2005a, 2007a).

A classic example is the demonstration of the concept of the transistor by Bell Labs in the 1950s. Proving the concept provided direction for applied R&D and reduced the risk associated with private-sector financial decisions to attempt the development of market applications. When this model is not followed, rates of innovation will be much lower, relying largely on the trial-and-error approach to produce an occasional breakthrough in the so-called Pasteur's Quadrant of innovation space.

Failure to understand and use this concept of technology platforms reduces the efficiency of innovation effort. A survey in 2006 by the National Center for Manufacturing Sciences (NCMS) of 600 companies led to the conclusion that "large-scale, market driven investments have been somewhat inhibited due to the lack of broader, in-depth understanding of nanotechnology's complex material-process-property phenomena and its interactions with humans and the environment". The NCMS analysis concludes: "Therefore, the near-term impact of nanotechnology is likely to be fragmented, product-specific, and evolutionary rather than revolutionary".[21]

Adopting an innovation model that ensures generic technologies are adequately developed provides the necessary transition phase between science and innovation. Large corporations have traditionally performed such research in the past and continue to do so. However, the complexity of new technologies, the shorter windows of opportunity brought on by compressed technology life cycles, and the trends toward specialization by individual firms in a limited set of technology applications and/or integration forward into services are combining to reduce corporate investment in new manufacturing technologies. Consequently, the so-called "valley-of-death" characterization that has been used to

[21] See "Nanotechnology Is Not Quite Ready for Prime Time," *Manufacturing & Technology News*, April 4, 2006.

connote the investment barriers increasingly faced by manufacturing firms at this critical phase of the R&D cycle is widening.[22]

An important example of the complexity of generic technology research is the required elements of the “post-CMOS” or “new logic switch” technology platform based on nanoelectronics:

- Concepts of new circuit design technologies based on the properties of individual molecules
- Generic fabrication methods for radically new classes of materials with unique electronic properties
- Generic methods for inducing novel compounds to self-assemble into the precise structures needed by new electronic devices and architectures
- Generic methods for interconnecting new devices into circuits

The third major element of an industrial technology, infratechnologies, also has strong public-good content. Infratechnologies, many of which provide the technical foundations for industry standards, are pervasive in the typical technology-based industry. Inadequate investment means that productivity suffers at all three stages of economic activity (R&D, processing, and commercialization). The multiple arrows from the infratechnology box in Fig. 6 demonstrate the ubiquitous and hence essential role played by this technology element.

For example, semiconductor design and manufacturing requires a large and diversified set of measurement infratechnologies that are applied directly to individual products and also to the highly automated production systems used in the modern semiconductor plant. A 2007 study by the National Institute of Standards and Technology (NIST) of measurement investment and its economic impact on the US semiconductor supply chain estimated that these industries invested $12 billion in measurement over the 10-year period, 1996–2006. This investment generated $51 billion in economic benefits for a net benefit of $39 billion.[23]

Measurement of the effects of nanostructure on product performance and processing techniques is fundamental to the design and manufacture of all nanomaterials and devices. Examples of infratechnologies supporting nanotechnology are

- Techniques for measuring the shapes, dimensions, and electrical characteristics of the various molecules making up nanoscale devices
- Techniques for manipulating and measuring the spin of individual electrons
- Scientific and engineering data for characterizing the fundamental physical behavior and long-term reliability of new nanoelectronic materials

The economic impact of this relatively unrecognized element of industrial technologies is substantial. Assuming that the remainder of what is commonly labeled as the “high-tech sector” invests in and benefits from measurement at approximately the same rate as has been estimated for the semiconductor supply chain by the NIST study, a rough estimate of the net economic benefits of measurement-related infratechnologies to this sector over the 10-year period is $455 billion (extrapolated based on shares of GDP). Yet, a number of economic studies by NIST document the significant underinvestment in the development

[22] More functionally referred to as the “risk spike”. See Tassey (2005a, b, 2008b).

[23] See http://www.nist.gov/director/prog-ofc/report02-3.pdf.

and use of infratechnologies and hence the negative implications for productivity growth without government investment.[24]

The most neglected and needy segment of manufacturing is the group of so-called "discrete parts" industries. This diversified set of industries will require radically new generic technologies to regain competitive advantage over manufacturing firms in other countries that have rapidly adopted existing automated manufacturing techniques. Major needed advances in generic technologies include

- Reconfigurable and agile manufacturing systems that can respond to ever shorter innovation cycles and rapidly adapt to customer demands for new products and new product features
- Multidiscipline-based manufacturing that combines physics, materials, engineering, and information technology to achieve state-of-the-art manufacturing precision, process optimization, and product functionality
- Advanced sensors, control systems, and wireless communications that provide immediate monitoring and reaction inside manufacturing systems to improve quality, decrease production cycle times, and eliminate waste
- Advanced non-traditional manufacturing techniques, including solid freeform fabrication (called additive manufacturing) and laser processing, to make innovative complex, custom products and replacement parts that are not realizable by more traditional manufacturing technologies or are required to be produced quickly in low volumes
- Smart assembly systems that pair skilled workers with helpful automation and robotics to reinvent how manufacturers put together products quickly and safely

A range of sophisticated infratechnologies will be also required, including

- Automated data synthesis and decision tools that process the high volume of product and process data from next-generation measurement systems for intelligent decision-making and manufacturing system optimization
- Modeling and simulation tools, interface standards, and reference data that can dramatically reduce trial-and-error, forecast costs and consequences of design and production decisions, and speed innovations to market

In summary, the policy importance of the multi-element model is that it (1) destroys the argument that government funding of *technology* research is "corporate welfare" and "picking winners and losers" and (2) much more clearly shows the effective leverage points for alternative policy instruments. For example, the public-good content of the "generic technology" and "infratechnology" elements of industrial technology make clear the need for government R&D support for these two elements. Without their explicit inclusion in the innovation model, inadequate support and inappropriate selection of policy instruments will frequently result. At a general level, the ability to characterize the specific barriers to investment associated with each element enables the selection of the most efficient policy instrument—tax incentives or direct funding (Tassey 2007a).

The "proprietary technology" element from which innovations are developed is a pure private good and hence the province of industry, but even private-sector R&D can suffer from market failures, although of a different type from the two quasi-public technology elements. Hence, different policy responses are required for each element and, as discussed in the next several sections, these responses will vary in time over a technology's life cycle. In general, this model is based on significant differences in investment incentives across

[24] See http://www.nist.gov/director/planning/strategicplanning.htm.

the three major elements and therefore provides a framework for the development of effective R&D policies.

10 The growth policy imperative: manage the entire technology life cycle

As indicated in the previous section, the multi-element model is necessary to accurately identify different types of underinvestment and match them with efficient policy responses, if a long-term and successful strategy for the manufacturing sector is to be realized. However, maintenance of competitive positions in global markets requires that this static framework be complemented with a dynamic construct so that adjustments to growth policies can be made as technologies mature and the nature of underinvestment changes.

That is, issues associated with being the innovator are only step one in a successful economic growth strategy. The United States has been the “first mover” and then lost virtually all market share in a wide range of materials and product technologies, including

- oxide ceramics
- semiconductor memory devices
- semiconductor production equipment such as steppers
- flat panel displays
- robotics
- video cassette recorders
- digital watches
- interactive electronic games
- lithium–ion batteries

Offshoring has become pervasive in that it has occurred in multiple tiers of high-tech supply chains (materials, components, equipment, subsystems). However, these declines, although large, have occurred slowly and unevenly enough to evade notice by many policymakers—until major aggregate market share has been lost.

11 Loss of manufacturing and R&D in the current technology life cycle

R&D policy must be managed based on the fact that technologies evolve in cyclical patterns with shorter product-technology cycles embedded in longer major cycles based on generic technology platforms. A key economic characteristic of this “nested” set of cycles is that the evolutionary pattern alters the nature of technologies and hence investment incentives. Private-sector investment reacts to these changing incentives and policy also must adjust. As pointed out in the previous section, the economic consequence of policy not taking cyclical investment patterns has been the loss of considerable domestic economic growth through offshoring of the markets for domestic innovations in the middle and later phases of these cycles.

Today, $1 trillion in global R&D and a rapidly growing skilled global workforce mean that no matter where a technology is first developed and produced, production has the potential to be progressively offshored from multiple tiers in the innovator’s domestic supply chain. When either a domestic company offshores production or when an indigenous manufacturing industry appears in another country, only a minimal amount of R&D is required in the host economy to enable product adaptation for local markets and to provide production support. Thus, the innovator economy initially loses value added primarily at the manufacturing stage. A superior domestic innovation infrastructure and the difficulties of competing economies in imitating it keep innovative activity within the first-mover economy—for a while. An example is semiconductors where manufacturing has moved offshore to a substantial degree, but indicators of inventive activity (as measured by relative patent rates) still show a US-centric pattern, especially for process technologies (Macher et al. 2008).[25]

Competitive pressures have led US-based companies to establish an increasing share of advanced wafer fabrication facilities ("fabs") outside the United States or to rely on foreign "foundries," (specialized manufacturing companies) rather than invest in the domestic US economy. A number have become "fabless" or "fab lite" firms, focusing on design while contracting most or all product manufacturing to foundries. While the fabless strategy is extolled by corporate consultants, it has evolved out of necessity as many semiconductor firms failed to achieve large enough market shares to capture scale economies at the production stage.[26]

A manifestation of this trend is evidenced by the fact that the US share of global semiconductor production capacity has shrunk from 42% in 1980, to 30% in 1990, to about 16% in 2007.[27] For the latest generation of wafer production technology (300 mm), the US share declined from 36% in 1999 to just over 20% in 2004. Two-thirds of new 300 mm fabs and approximately 80% of all 300 mm fabs under construction are outside the United States, primarily in Asia. Yet, US-headquartered semiconductor producers still dominate global sales with 48% of worldwide markets and remain the undisputed technological leaders. Thus, one can understand how economists and other analysts, by focusing on current market shares of US-headquartered companies, misinterpret current trends.

Fabless semiconductor companies have been successful in the current mature phases of the CMOS technology life cycle by adopting highly accurate simulation techniques that drastically reduce the number of expensive and time-consuming iterations of the product design necessary to enable its manufacture. Dedicated foundries, in turn, often do not even operate development-scale fabs, instead relying on real-time adjustments. Both of these single-stage strategies can work within the middle and latter phases of a particular technology's life cycle.

However, when major technological change occurs (that is, when a major new technology life cycle begins), both strategies will hit a brick wall. The fabless firms will not be able to execute design for new manufacturing requirements without close interaction with manufacturing scale-up activity and foundries will not be able to adapt to radically new product technologies without close interactions with the ongoing product R&D. In the long run, the threat to the US domestic industry is the growing ability—and willingness—around the world to backward integrate to the underlying science itself, especially for the next major (post-CMOS) technology cycle.

In fact, as emerging economies get a taste of the higher value added attainable first through assembly and later through component manufacturing, their growth strategies begin to shift toward R&D aimed at new designs and eventually next-generation versions

[25] The segmentation (horizontal disintegration) of domestic R&D and manufacturing and the subsequent loss of the entire tier is the first part of the process off shoring high-tech supply chains. See Pisano and Shih (2009) for a number of examples.

[26] For an example of support for the fabless strategy, see Doraiswamy (2006).

[27] From several sources. See Dewey and LeBoeuf LLP (2009, p. 14).

of the generic technology. In the Chinese semiconductor industry, backward integration has included a substantial share of design work that is being driven by (1) the rapid double-digit growth rate of that country's domestic market for semiconductor devices, which now accounts for about one-third of the world's consumption,[28] (2) the emergence of skilled design engineers, and (3) the desire to move up the value-added ladder as a supplier of semiconductor technology. While the current level of design is not yet world class, the Chinese are aggressively pushing toward the next and final step in the convergence process, which is to become a developer and exporter of semiconductor components. Other Asian economies, such as Taiwan and Korea, are further along in this process. In fact, both Korean and Taiwanese firms have not only become integrated device manufacturers, but they are progressively integrating forward into consumer electronics.

As a result of these trends, an increasing share of US semiconductor companies' product-design R&D is being located outside this country. As new electronic product markets have emerged, both designers and manufacturers of semiconductor-based systems (e.g., wireless communications and consumer products) are increasingly concentrated in Southeast Asia due to co-location synergies (Ernst 2005).

Further, in the tier of this supply chain beyond semiconductor devices are manufacturers of subsystems of multiple devices. This industry provides a stark example of how fast economic activity, even in technology-based industries, can shift to other economies. In 2000, nearly 80,000 workers were employed in the North American printed circuit board industry; but by the beginning of 2004, employment had dropped to just over 41,000 (National Research Council 2005). Since then, employment has continued to drop (McCormack 2009). In summary, the sequential loss of market shares from multiple tiers collectively means a steady hollowing out of valued added from the domestic semiconductor supply chain.

The bottom-line points for growth policy are (1) value added has moved backward in supply chains, implying that more high value-added domestic economic activity is lost when component manufacturing is offshored, and (2) co-location synergies not only protect the value added created by multiple tiers in a domestic high-tech supply chain, but in many cases, especially early in a technology's life cycle, they seem to increase total valued added due to the efficiency effects of co-location.

The process of convergence among national economies can be explained by the fact that the R&D capability established to manage the offshored manufacturing serves as the genesis of a nascent innovation infrastructure. Along with investment in broader research capabilities by the government, a capability evolves to be the "first mover" for emerging technologies that drive future life cycles. Taiwan is achieving backward integration from test and assembly to wafer fabrication to design (the integrated device manufacturing model). Both Taiwanese industry and government now participate in global R&D networks. Taiwan's Technology Research Institute (ITRI) has research collaborations with companies, universities and governments all over the world. This is clearly a leading-edge technology strategy. While further behind in the convergence process, the Chinese are following the same backward integration path. Patent trends in nanoelectronics clearly show the threat of convergence early in the next life cycle to be real.

[28] Chinese semiconductor consumption in 2007 was $88 billion (34% of the world's total consumption of $256 billion). In keeping with the process of convergence, domestic production is being stimulated by the large domestic consumption of chips. China's domestic production of semiconductors increased from 2% of the world's total in 2000 to 9% in 2007. Source: Semiconductor Industry Association and PricewaterhouseCoopers.

The threat to US technology leadership is actually greater in other areas where high-tech industries remain more vertically integrated than in semiconductors. In the flat panel display (FPD) industry, for example, design and manufacturing are still highly integrated. A few US FPD firms (mostly small niche-market firms) have remained competitive by maintaining relationships with Asian manufacturers, but the co-location synergies are strong and most innovative activity has followed manufacturing to Asia. Meanwhile, US R&D capability has eroded due to declining US Government support (Hart 2008).

By exiting the FPD industry, US-based companies are not competitive in polysilicon-on-glass technology that is prominent in newer electronic devices, such as e-readers and recent iPhones. This glass/silicon substrate innovation only succeeded after years of iterating the technology among Asian manufacturers (Shih 2009). Thus, the vertically integrated high-tech supply chain is likely to be the growth model going forward. The importance of this strategy is largely ignored in the United States.

However, even analysts who have thought in depth about this supply-chain integration issue continue to disagree. Pisano and Shih (2009) support the position that the offshoring of the semiconductor supply chain is a negative for long-term US economic growth. Shih (2009) separately reinforces this position by analyzing the global distribution of the sources of the components of the Kindle e-reader, which Amazon designed. One of its key components—the "electronic ink" (tiny microcapsule beads used in the Kindle's electrophoretic display) was developed and is currently manufactured in the United States by a small company, E Ink. The sources of all other electronic components in the Kindle—both R&D and manufacturing—are outside the United States. The estimated cost of the Kindle is $185. Of this amount, $40–$45 is estimated to be captured within the US economy, mostly by Amazon. Moreover, although the display is the single largest component in terms of cost, E Ink has to have the glass/silicon substrate made in Asia, so it does not capture the full market value of the display. The company's inability to produce the entire display significantly limits its potential value added to the domestic economy. In fact, the limited growth potential had forced E Ink to attempt to sell itself to Prime View International, the Taiwanese company that manufactures the display incorporating E Ink's special beads. Such a merger could result in E Ink's R&D and manufacturing activities being moved to Taiwan.

Another example of the global distribution of the sources of value added from a consumer electronic device is Apple's iPod. In depth analysis showed results similar to those obtained for the Kindle. The study estimated both the cost of components and the gross profit earned by each supplier. Again, the vast majority of the value of all manufactured parts is now offshored (Linden et al. 2008).

The counterpoint to the negative view of offshoring high-tech manufacturing is that companies like Apple and Amazon have become highly successful by focusing on design and forward integration into related services. It is certainly the case that these two companies are capturing significant shares of the value added. Moreover, Apple has prospered since it gave up its highly vertically integrated strategy. By outsourcing all manufacturing, the company has greatly increased its performance (Yoffie 2009). Further, the Apple business model is considered to be sustainable over time because the company along with others such as "Amazon, Google, Hewlett-Packard, IBM, AT&T, and Qualcomm have successfully used their investments in software, services, infrastructure, and intellectual property to do the same. All use their market power to force upstream vendors to invest for them to make the inputs to downstream innovations … cheaper and more plentiful" (Rappaport 2009).

It is true that Apple captures a large share of the iPod's value added. An analysis by Portelligent Inc. estimated that Apple's gross profit margin was 34% of the estimated wholesale price—resulting in greater value added than for any of its suppliers (Linden et al. 2008). And, for units sold in the United States (about half the total), portions of the retail price went to distribution and retail firms, further adding to domestic value added.

As is the case for many innovations, the iPod initially had little competition, in part because of its innovative design and in part because Apple was able retain a monopoly on the sale of songs to iPod owners. Controlling the supply of music allowed Apple to cut the price of the iPod and sell even more units. However, as Rappaport (2009) admits, "this model breaks down … where US companies and innovators do not naturally control downstream demand." As the United States has only 4.5% of the world's population, the post-WWII model of a global economy led by the US consumer was living on borrowed time and, in fact, is now defunct.

Even if Apple maintains its market dominance through the entire technology life cycle, the finite life of the iPod's product technologies makes it hard to argue that such a strategy can be characterized as a model for large-scale application and hence a long-term driver of domestic value added.

Finally, Apple has other somewhat unique competitive attributes. The company develops its own software and has superb management. This tacit knowledge implies a co-location strategy, which means Apple's operations will likely stay in the United States. While this is a good thing for the domestic economy, the growth policy question is how many Apples can be successful at the singular design stage of economic activity. Because Apple has residual tacit knowledge associated with the electronic components in the IPod from its history as a vertically integrated company, it had a competitive advantage in designing the product. In contrast, although Kindle was an initial market leader, Amazon lacked similar product technology expertise, which has shown up in the rapid imitation by other companies, including foreign companies. Even for Apple, however, the next generation of electronics technology will be foreign to the company and quickly dilute its current advantage.

Apple's strategy might remain viable over more than one technology life cycle by establishing development partnerships for next generation hardware and software; i.e., through immersion in a technology cluster. However, without the internal research experience and hence expertise, such a strategy will be difficult to execute. Apple's forward integration into services is fairly simplistic—sell songs to iPod owners—and, in fact, Apple does not appear to have made much of a profit from the iTunes Music Store. Thus, their business model would seem to depend largely on the continued dominance by iPod of the MP3 player market.

In contrast, IBM arguably has the most complete vertical-integration strategy of any IT company in the world. Its long-term research facility, the Watson Research Center in Westchester, NY, is close to the company's semiconductor R&D and 300 mm manufacturing facility in Fishkill, NY. Its large computer systems manufacturing and assembly operation is just a little farther north in Poughkeepsie, NY. Albany is the center of IBM's post-CMOS research activity. These facilities are all within half a day's drive, which enables the needed intense co-location synergies for innovative product and service development.

However, the evolution of IBM's corporate strategy over the past two decades leads some to argue that the US economy is moving justifiably toward a total service economy. The proponents of this view may want to reexamine this alleged natural progression of the high-tech economy. High valued-added, high-tech services are complex systems. The design of such systems requires bundling a wide range of hardware and software technologies. Not being intimately involved in the ongoing development of these technologies through participation in the R&D stage or, at a minimum not attaining close association with suppliers of such technologies, will not be a successful business strategy in "the service economy" of the future. In fact, IBM has shown no indication of winding down its highly productive product R&D facilities. IBM may be somewhat of an outlier in that it is one of the most vertically integrated R&D-intensive companies in the world. However, the technology cluster model works for decoupled high-tech supply chains, as long as the supporting infrastucture is supplied.

An important aspect of life-cycle management is the fact that all large R&D-intensive companies are global in scope. 71% of IBM's employees are located outside the United States because (1) IBM understands the need for co-location synergies at the national market level and (2) the company increasingly can find quality research and manufacturing infrastructures in other countries that support the increasingly essential technology cluster model.

The policy implication is that investment location decisions are increasingly being made not solely on near-to-market considerations, as was the case several decades ago. Rather, they are being made on the availability of an increasingly complex infrastructure. The New York technology cluster includes many small and medium firms, state-of-the-art university research facilities, and skilled labor. To date, however, such clusters have appeared in the US economy almost exclusively where state governments have supported them.[29]

Responding to these trends is complicated by the need in such complex technologies for an equally complex set of infratechnologies (supporting technical infrastructure) associated standards. Research on such technical infrastructure is now often done at geographically separate locations, but in the future it will have to be an integral part of research clusters.

In addition, vertical disintegration is unlikely to work for new technologies because fabrication processes have only been partially characterized. For example, emerging MEMS ("micro-electromechanical systems") technology requires a more sophisticated fabrication process than do integrated circuits, involving the interaction of phenomena from a much larger set of physical domains: electrical, mechanical, thermal, optical, fluidic, and more. Fabrication processes have not yet been adequately characterized with respect to these multiple physical domains.[30] Therefore, co-location of R&D and production is essential. Without co-location, the design-for-manufacturing imperative will not be realized.

Thus, a major policy point is that viewing the hollowing out of a domestic supply chain over a technology's life cycle as simply a matter of specialization according to the law of comparative advantage is turning out to be naïve in that not only is value added lost but co-location synergies often convey growing and permanent competitive advantage to those economies that adopt an integrated technology development and utilization model.[31] As demonstrated by evolving national technology-based growth strategies around the world, the public–private asset character of modern technologies is leading both government and industry to not only up the amount and type of R&D but to do so using more efficient collaborative research methods.

[29] The federal government's first program to support regional innovation clusters is a $50 million FY2010 budget request for the Department of Commerce's Economic Development Administration.

[30] MEMS technology has already produced new higher-performance products such as accelerometers for automobile airbags, tiny nozzles for ink jet printers, and projectors for high-end video displays. Continued commercialization of MEMS technology has been forecast by some analysts to produce a second semiconductor revolution that will drive growth in the US economy for decades to come.

[31] The phenomenon of co-location is not just about the provision of complementary technology assets and the efficient transfer of technical information but also includes benefits from institutional integration (Hermans et al. 2008).

12 Loss of R&D and new manufacturing in the next technology life cycle

The transition between two technology life cycles is at least as difficult a policy challenge as managing the entirety of a single life cycle. This problem of cycle transition is accentuated the more the technologies underlying successive cycles are different. Technologies based on different science require different technology development and production approaches. Both the R&D and production capital infrastructures within the industry will need to change. In fact, the entire supply chain in which the industry is embedded will likely be different.

The contrast between the traditional pharmaceutical industry and the emerging biotechnology-based industry is a case in point. The existing industry has sunk an enormous amount of resources into a small-molecule chemistry from which drugs are "discovered" through a largely trial-and-error approach. Even sophisticated research techniques such high throughput screening only modestly increase the efficiency of a very inefficient R&D approach. The declining relative efficiency of this industry is evident in the increasing reliance on marketing (the industry spends more on advertising than on R&D).

In contrast, the biopharmaceutical industry is based mainly on the development of large-molecule drugs derived from a fundamental underlying science (cell biology). The greater efficacy of biopharmaceutical products sells them, not advertising. The dependency of biopharmaceuticals on a complex science base demands the use of the multi-element technology model to achieve R&D efficiency. However, NIH funding has been primarily directed toward basic science on the assumption that scientific advances will attract venture capital with the result being innovative new drugs. This approach is an application of the black-box model of innovation. As a result, while new biopharmaceuticals have resulted from private-sector R&D, the productivity of this investment has been low.[32] Such results are finally turning the biopharmaceutical industry toward the multi-element technology model. In the last few years, research has increasingly emphasized proof of concept and improved infratechnologies, such as biomarkers (Haberman 2009; Gallaher et al. 2007).

The major policy response in an increasing number of economies is the technology cluster concept, which is emerging as an important institutional strategy for not just efficiently conducting breakthrough research but also to increase the efficiency of subsequent commercialization. For example, the Nanoscale Science and Engineering cluster at the University of Albany not only conducts proof-of-concept research, but also provides "quick turn-around capability" to support the increasingly difficult first-stage fabrication cycle and thereby allow "seamless transition to high volume industrial manufacturing after the demonstration of feasibility stage."[33] The bottom line is that achieving co-location synergies means the value added from both R&D and manufacturing will accrue to the innovating economy—at least when the technology is in its formative stages.

Similarly, integrated semiconductor firms operate "process-technology development" facilities to debug new manufacturing technologies. Typically, the development fabs are located in the innovating semiconductor firm's home country. The demanding technical nature of state-of-the-art innovation requires close coordination between product design

[32] Since the mid-1990s, the number of new drugs approved per year has declined, while the cost of taking a drug candidate from discovery through FDA approval has increased. This means that from a portfolio perspective, a successful drug must cover not only the growing total cost the portfolio R&D, but also the costs of an increasing number of failures.

[33] See http://cnse.albany.edu/ContentManager/index.cfm?Step=Display&ContentID=172.

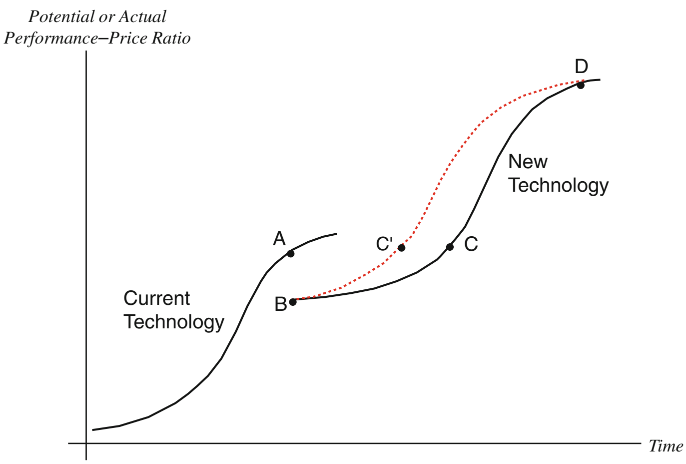


Fig. 7 Life-cycle market failure: generic technology

and process-technology development and also between process-technology development and commercial-scale operations.[34]

The policy imperative is to manage the transitioning of domestic industries from one major technology life cycle to the next faster and more efficiently than foreign competition. The barriers to such cycle transitions are indicated in Fig. 7. As the current technology (left curve) matures, all product attributes and hence performance are improved. Costs are reduced through optimization of production processes. Eventually, the industry approaches a maximum performance-price ratio for the technology based on the inherent limitations of the underlying generic technology (point A), which explains the flattening of the top portion of the s-shaped growth curve.

Such a "cash-cow" status and the investments made to achieve it act as barriers to private-sector investment in emerging technologies that have greater potential but initially have significant performance deficiencies. Companies do some long-term research in anticipation of eventually having to shift to a new generic technology platform. However, life-cycle compression due to increasingly intense global competition reduces risk-adjusted expected RoI and thereby leads to substantial underinvestment. The multi-element technology model identifies one of the major causes of underinvestment in addition to the existence of higher discount rates—the public-good content of both generic technologies and infratechnologies. A third major reason is the lack of an adequate innovation system that emphasizes R&D efficiency strategies such as technology clusters and a portfolio method for allocating R&D resources. These last two reasons explain the flat bottom portion of the s-shaped growth curve.

Traditional R&D (black-box) models result in reduced and/or premature attempts at innovation. These efforts typically encounter multiple performance problems that are only addressed over time. Moreover, small initial markets for the emerging technology do not induce significant process technology investment. The consequent suboptimal production

[34] For example, semiconductor manufacturers now create multi-function "systems on a chip" that can yield greater innovation impact than traditional single-function chips. However, doing so requires close interaction with downstream electronic product companies and other users to define R&D objectives.

processes result in relatively high unit cost. The combined result is a lower initial performance-price ratio (point B) than is the case for the current mature technology.

From an R&D investment perspective, the prospect of such an initial performance-price gap leads the private sector to assign substantial technical and market risk to the possibility of investing in the development of the new technology. This "risk spike" (commonly referred to as the "valley of death") results in underinvestment by the private sector in early-phase generic technology research. The collection of barriers facing private firms at this early point in the R&D cycle creates the need for government support, not just for basic science but for early-phase, proof-of-concept (generic) technology research and a range of infratechnologies that leverage the efficiency of this research (Tassey 2007a, 2008a, b).

Most industrialized nations now have innovation-system programs to reduce the risk spike. These efforts include not only R&D subsidies but, more recently, promotion of more efficient R&D mechanisms, especially various forms of research collaboration. The most advanced form of collaboration, R&D clusters, can not only enhance research efficiency in general, but also significantly increase co-location synergies between adjacent tiers in high-tech supply chains. The impact of policies aimed at increased R&D and R&D efficiency is a shift in the domestic performance-price curve upward and to the left (the dotted line in Fig. 7). Thus, a performance-price ratio equivalent to the cash-cow position of the existing technology is reached faster (C′).

13 An example of life-cycle offshoring: battery technology

Energy storage has been cited as the driver of systems-level technologies in such disparate areas as electrical power production/distribution and consumer electronics. In the latter case, evolution of technology life cycles has resulted in new generations of wireless devices and portable entertainment products. Such products are making greater power demands on batteries. Reductions in operating voltage have done little to offset the problem because new generations of products have extra features (examples: color displays, speech-recognition capability, electronic banking, and a range of information and entertainment services) that increase the burden on energy storage technology.

Most portable consumer electronic products use disposable batteries, which are a mature $18 billion global market. Not only is a market of this size attractive but the proliferation of electronic devices means continuing growth in demand. However, standardization imposed by device manufacturers on the previously dominant alkaline technology has restricted even modest innovation. Specifically, options for new chemical compounds have been constrained by the requirement to 'fit' the battery into the standard shape. It is through such constraints in the later phases of a life cycle that the legacy of past investment strategies has its greatest and often terminating effect on the existing industry structure.

This portion of the creative destruction process is characterized by the market-share leaders pouring enormous resources into minor improvements. Meanwhile, a radically new technology is lurking in an unseen location elsewhere, so that incumbents eventually become victims of what has been called "motivation asymmetries" (Christensen et al. 2004a).

A critical aspect of this process is the tendency of dominant companies to find ways to ignore the inroads in their markets by new entrants who are both more desperate and uninhibited by the current technology and market focus (i.e., the latter are unaffected by the installed-base and installed-wisdom effects). The new entrants may initially focus on the low-value-added market segments, which are beneath the dignity of the incumbents. However, through innovative technology and marketing strategies, these upstarts move up the value-added scale and encroach upon or, in some cases, grab large shares of the existing major markets. In the latter case, the incumbents frequently are put out of business.

In the early 1990s, lithium–ion batteries were developed as a challenger technology. A distinguishing feature is that they are rechargeable. As a result, they have become the standard for high-energy, rechargeable batteries. Moreover, they have four times the energy and twice the power capacity of competing nickel cadmium (Ni–Cd) batteries. They also do not experience a memory effect (the loss of energy storage capacity that results from partial discharges before recharging).

As described in an excellent paper by Brodd (2005), American companies, having succeeded in reaching the leadership position in disposable batteries through realization of economies of scale in production, brand imaging and superior marketing, have not been able to adapt to the new technology life cycles for rechargeable batteries. A disposable battery is a standardized commodity and hence so is its interface with the electronic products it powers. This situation allows battery manufacturers to operate in a non-integrated way within the device supply chains they serve. Co-location synergies are not important.

This is not the case for newer rechargeable battery technologies. Development of Li-ion batteries has required close contact with portable electronic device designers to adapt the battery to the performance attributes of the device. Large American battery manufacturers, such as Duracell and Eveready (now Energizer Holdings), began R&D efforts to develop the new technology in the early 1990s. Their intent was to ultimately commercialize and domestically produce Li-ion batteries. However, as Li-ion battery technology emerged, lack of scale and initial production inefficiencies discouraged these companies from investing in production facilities in the United States. Labor costs were not a factor in this decision. The highly automated unit cell production process for the new technology offset any labor cost advantage of locating production in East Asia.

The lower profit margins typical of the early phases of a technology's life cycle coupled with the higher profit margins of mature disposable batteries acted as a disincentive to US manufacturers to invest in the capacity to produce the new rechargeable batteries. Typically, the defenders of the old technology attempt to remain competitive by continually cutting costs. However, cutting costs for production based on an increasingly obsolete generic technology is a doomed strategy. The installed-base effect was in full force in the American battery industry.

Success in the rechargeable market requires knowledge of the electrical requirements for emerging products that require these batteries, as well as the ability to achieve rapid product improvements to meet changing device requirements and then to assemble the unit cells into battery packs for use in specific devices. Most producers of portable electronic devices are located in Japan and are vertically integrated companies; that is, they are both producers and users of Li-ion batteries. In contrast, most US manufacturers lack the ability to integrate with upstream design firms and materials suppliers and with downstream customers; that is, supply chain integration is not present in the US market.

Moreover, effective supply-chain integration, in addition to communication, requires an understanding by large manufacturers that smaller suppliers need both adequate profits and some minimum level of orders during down portions of the business cycle to sustain R&D and update productive capacity. However, the strong profit-maximization focus by US companies, in contrast to a greater emphasis on market share and sustainability by, for example, Japanese companies, has led to further hollowing out of the US supply chain. Finally, even though several US companies have the capability to produce all the components and materials associated with Li-ion technology, no viable market exists in the US economy because all the manufacturing takes place in Asia (Brodd 2005).

Current US research in battery technology is investigating the potential of a range of new energy sources, including ceramic, kinetic, photovoltaic, electrochemical, thermal and biological technologies. For example, attaining the ability to deposit microbatteries directly onto printed circuit boards would provide a significant competitive advantage over stand-alone batteries—an advantage that manufacturers are keen to exploit. Unfortunately, printed circuit boards are now produced largely outside the United States, which again inhibits supply chain collaboration.

In the past few years, a number of venture-backed startups—Boston Power, International Battery, Valence Technology, Altair Nano, A123 Systems, PowerGenix, ZPower—have appeared (Kanellos 2008). However, US battery R&D is still largely dispersed and uncoordinated—another example of the traditional non-portfolio and non-supply-chain approach to R&D funding. And, it is not as if attempted innovation in battery technology is only occurring in the United States. Samsung, for example, is developing a direct methanol fuel cell as part of a docking station that allows a notebook computer to run for 8 hours a day, 5 days a week, for up to 4 weeks (Garrett 2006).

Recently, however, a US advanced battery consortium (officially, the National Alliance for Advanced Transportation Battery Cell Manufacture) has been formed. It was created in 2008 as a collaboration among 14 companies and Argonne National Laboratory and has asked for $1 billion in government funding. Moreover, the US government recently implemented an initiative to promote a domestic automotive supply chain for the forthcoming era of electric and plug-in hybrid vehicles by announcing subsidies for battery plants.[35]

While implementation of the research consortium model and efforts to promote supply-chain synergies are steps in the right direction, Asia, by virtue of an already established concerted public–private effort, has a better research infrastructure and a more efficiently integrated supply chain. Thus, it remains ahead of the United States in battery science, technology, and manufacturing through a better national innovation system. The policy imperative is to use modern research portfolio methods and pursue supply-chain integration and also to implement such strategies in the right time frame relative to the technology life cycle.

14 A technology-based manufacturing strategy

Because manufacturing accounts for the majority of industrial R&D, its future strongly depends on more efficient government R&D policies that leverage industry investment in accordance with the public–private nature of the multi-element technology growth model.

[35] Compact Power Inc. is a subsidiary of South Korea's LG Chem. Korea is where much of the current world's supply of advanced automobile batteries is located.

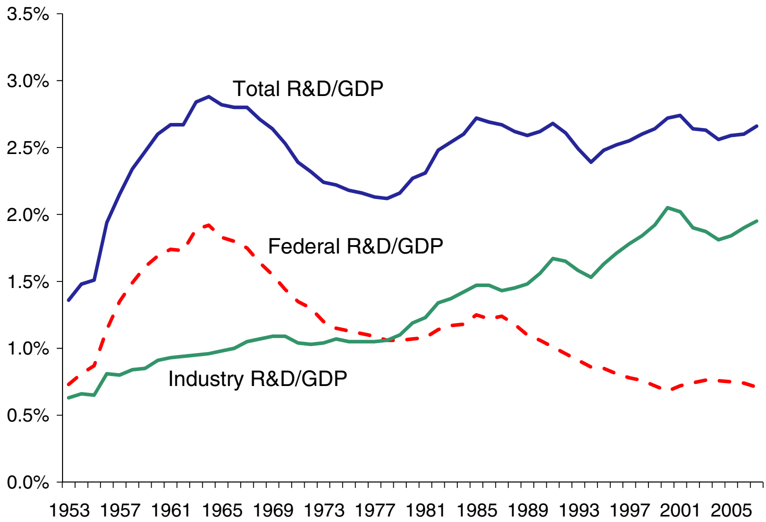


Fig. 8 R&D intensity: funding as a share of GDP, 1953–2007. *Source*: National Science Foundation

Based on discussions in the preceding sections, an R&D policy for manufacturing must be built on and judged by assessments of the required

- amount of R&D
- composition of R&D
- distribution of R&D among tiers in the high-tech supply chain
- efficiency of R&D programs

14.1 Amount of R&D

Perhaps more than any other indicator, the long-term trend in US R&D intensity represents the lack of adaptation to the changing global economy. Figure 8 shows that the R&D intensity of the US economy is virtually the same today as in 1960. During the intervening five decades, the global economy has become far more R&D intensive. The United States still accounts for about 30% of global R&D, but its share is shrinking. With 4.5% of the world's population, a small high-tech sector (approximately 7% of GDP) and a trend toward private-sector offshoring of R&D, this negative trend will continue and possibly even accelerate.

The Obama Administration has set a goal of a 3% R&D intensity. Achieving this ratio would be a record high for the US economy (slightly exceeding the average of high of 2.8% in the mid-1960s), but this ratio would only tie Korea for fifth place among technology-based economies (Fig. 4).

14.2 Composition of R&D

From a national innovation system perspective, the main culprit with respect to both aggregate underinvestment in R&D and suboptimal composition of this R&D is the federal government. Figure 8 shows that the federal share has declined significantly over five decades. In contrast, US industry's share has increased steadily—at least until this decade, during which it has actually declined, in part due to increased offshoring.

The manufacturing sector's R&D intensity (industry-funded R&D/sales) began growing slowly in the mid-1980s from approximately 2.5% to the current rate of 3.7%. The increase has been a response to globalization, but this "response" is more the result of offshoring low R&D-intensive industries than to absolute increases in R&D spending. More important, this average intensity pales compared to truly R&D-intensive industries, whose ratios of R&D to sales range from 8 to 22%. Most of the global economy's R&D is targeting manufacturing technologies and is growing rapidly, clearly posing an increasing competitive challenge for individual nations.

Nanotechnology is a prime example. Unlike past major disruptive technologies, the United States does not dominate the world's R&D effort. North America, Europe and Asia each account for about one-third of the estimated global R&D spending on nanoscience and nanotechnology research of $14 billion.[36]

The federal government was once the dominant sponsor of the nation's R&D, funding 65% of all US R&D in 1965. But the federal share moved downward in the subsequent 3 and one-half decades to a low of 25% in 2000 and was only slightly higher at 27% in 2007. This declining share for federal R&D funding is particularly evident in the business sector. In the late 1950s and early 1960s, more than half of the nation's business R&D was funded by the federal government, but by 2000, less than 10% of business R&D was federally funded. Government-funded manufacturing R&D increases the sector's R&D intensity from 3.7 to 4.1%—hardly enough to qualify the sector as "R&D intensive."

Adherents to the black-box model of technology-based growth might argue that this trend is actually positive because all technology development is the province of the private sector with government only funding basic science. In this context, a higher ratio of industry to government R&D funding would likely be judged as providing more leverage for the government investment in the science base.

Such a view inaccurately represents the modern technology-based economy because it does not take into account the quasi-public-good content of technology research with its implications for the correct balance between public and private funding for R&D. In fact, not only has aggregate federal R&D funding not kept pace with the needs of the US economy, but data show that the "S&T" and "nondefense" portions of the federal R&D budget have not grown at all in real terms in recent years, further accentuating the decline in federal support for emerging manufacturing technologies and supporting technology infrastructure. Support for these two categories of technology research are absolutely essential to leverage the efficiency of industry's investments in innovation.

Figure 9 shows the trends in the "R" part of R&D spending. Overall federal S&T funding grew rapidly between 1998 and 2004, but this growth was largely due to a doubling of the NIH budget (even in inflation-adjusted terms). S&T research support for other areas of technology has been weak, growing at an average annual rate of just 1.1% over the past 20 years and, in fact, declining in real terms over the past 5 years. It is this portion of the federal S&T budget that supports new manufacturing technologies.[37] The bottom line is that the slow (and, in fact, recent negative) growth of R&D funding for breakthrough manufacturing technology research is a serious policy concern.

[36] President's Council of Advisors on Science and Technology (PCAST), *The National Nanotechnology Initiative: Second Assessment and Recommendations of the National Nanotechnology Advisory Panel*. Washington, DC: April 2008. The global nanotechnology R&D estimate is from Lux Research.

[37] Even including NIH funding, federal S&T research has declined in real dollar terms since 2004.

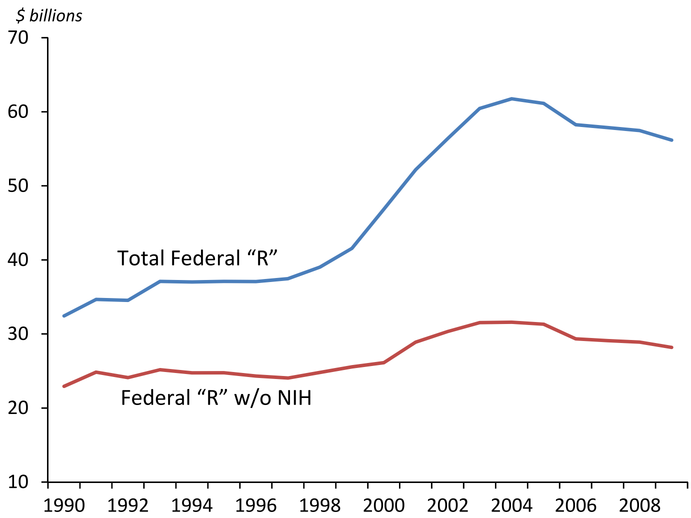


Fig. 9 Federal research ("R") funding: 1990–2009 constant 2008 dollars. *Source*: AAAS. *Note*: FY2009 does not include stimulus funding

The economic growth paradigm that served the US economy so well for decades was based on a stream of 'technology platforms' (generic technologies) funded in part by government and originating in the industrial laboratories of large companies (AT&T's Bell Labs, Xerox's PARC, RCA's David Sarnoff Research Center, and other). Those days are gone. Internal long-term corporate research has been cut back and redirected toward shorter-term objectives, in particular, support of current technology-life-cycle strategies and evaluation of external sources of technology. In its place, major innovations are increasingly being spawned from collaborations of various types, including spinoffs from universities and federal laboratories. An increasingly large percentage of these innovations are federally funded (Block and Keller 2008). Yet, federal funding of R&D has declined relative to GDP for decades and the federal R&D establishment is dominated by agencies whose missions are public goods other than economic welfare.

The overriding policy question is how to expand and improve the efficiency of this increasingly complex and diversified innovation ecosystem, so as to effectively nurture a portfolio of breakthrough technologies that will create new markets, industries and jobs within the US economy. US-headquartered corporations will still get access to breakthrough technologies through global research collaborations, but they are increasingly doing so by partnering with foreign companies and governments. The resulting intellectual property will be partially owned by companies outside the US economy and therefore so will much of the valued added activity that results from the new IP. While participating US companies will have rights to this IP, they are increasingly allocating subsequent applied R&D (innovation investment) and production investment to other economies.

Thus, government policy makers have to worry not only about inadequate amounts and types of government R&D funding but also the growing globalization of corporate R&D, which means that the historic steady growth of domestic corporate R&D investment is no longer assured. CEOs of US-based companies have stated on numerous occasions that their companies are truly global in that not only are manufacturing and marketing operations being offshored, but R&D is now also globally dispersed, as well. IBM has approximately 400,000 employees of which 71% are now located in other countries, including many engaged in R&D. GE gets more than 50% of its sales from markets outside the United States, and so on.

The other major element of an industrial technology, infratechnology, is poorly understood and hence investment in this essential infrastructure is often both too little and poorly timed. This underinvestment persists in spite of numerous studies that show large economic impact through efficiency enhancements of R&D, production, and commercialization. As discussed in the next section, a diverse set of infratechnologies will have to be an essential part of a technology-based manufacturing policy.

Adequate investment in these two elements of an advanced manufacturing technology system offers the potential for the US economy to attain global leadership through the ability to produce high-quality, low-cost products—even in very small lots. That is, the most advanced manufacturing sectors of the future will be able to basically eliminate economies of scale, which characterized the industrial revolution. Instead, the emphasis will be on maximizing economies of scope. In other words, the ability to mass-customize products for a wide range of increasingly sophisticated and demanding customers and produce them cheaply in small lots will provide the competitive edge in the future.

14.3 Supply-chain R&D strategies

As the previous section argues, the first and most global policy change needs to be the adoption of the view that policies to restructure manufacturing for long-term competitiveness are a "supply-chain" problem, not an "industry" problem. For example, debating alternative strategies for resurrecting the "Detroit Three" as opposed to revitalizing the entire automotive supply chain will yield disappointing results.

When technologies are new, they are often provided in their entirety by a small number of innovative firms. As technologies mature, vertical disintegration occurs as a natural consequence of expanding markets and the diversifying nature of competition in which variety, price, and quality emerge as important attributes along with the original driver of demand—performance. Specialization is a natural consequence of growth and standardization of at least some elements of product technology. The backward decoupling effect results in distribution of R&D to the earlier tiers in the supply chain and thereby distributes high-valued-added opportunities, as well.

When this does not happen, the domestic economic benefits potentially realized over the technology life cycle can be constrained and even eliminated to the detriment of the incumbent firms and the economies where they are located. The minicomputer was largely comprised of hardware components and software from the minicomputer companies themselves. The persistence of vertical integration restricted mid-cycle innovation and helped open the door to the emergence of the PC, which through standardized component interfaces could be built from parts supplied by multiple vendors in a vertically separated supply chain. This led to the entry of a wide variety of innovative companies such as IBM, Seagate, Dell, and Microsoft who collectively created a huge global PC market.

However, markets structured along the lines of the PC accelerate "backward decoupling." Rather than isolation of the tiers in a high-tech supply chain, vertical disintegration leads to a need for more, not less, coordination. Vertical distribution of R&D is part of the expanding phenomenon of open innovation, which involves greater levels of collaboration. Unfortunately, once offshoring has begun, the need for such collaboration often leads to offshoring of multiple tiers due to greater co-location synergies in the second economy.[38]

No matter what the final outcome with respect to distribution of value added in one technology life cycle, global markets are up for grabs in the next life cycle for all economies with the requisite innovation infrastructure, as evidenced by the fierce battle currently underway for first-mover advantage in nanotechnologies. For today's science-based technologies, innovating and then acquiring market share in the early phases of major life cycles require large numbers of scientists and engineers both in industry and supporting university and government institutions to advance and broaden the applications of the original innovation. For example, cell-based drug development has evolved as a research and manufacturing technique over the past 25 years only through the efforts of thousands of biologists, geneticists, and chemical engineers who perfected the fermentation systems that increased the capacity to produce recombinant proteins at least tenfold just in the past decade and 30-fold since the inception of biotechnology (DePalma 2005). The efficiency with which this process unfolds is not just a matter of private-sector R&D investment but depends greatly on the efficacy of the entire innovation infrastructure.

14.4 R&D efficiency

A steadily increasing number of economies now develop high value-added products. Korea, for example, has risen to the world's 12th largest economy by steadily increasing manufacturing R&D. That economy's progress has been leveraged by major national projects, such as a 10-year, $200 million collaborative R&D effort involving six research institutes, 27 universities and 70 companies to advance computer-integrated, flexible manufacturing systems. The Koreans claim that the project has increased productivity growth for the involved companies by 300%. In addition to such process technology gains, Korea has emerged as an innovation leader in high-definition television and CDMA mobile phone technology. Korea's Hyundai has joined Toyota and Honda as the three leading global automobile companies with respect to quality, according to JD Power & Associates.

The potential R&D efficiency gains from collaboration depend not only on the management of hardware and software R&D among the tiers of the supply chain but also require coordination with the sources of a diverse technical infrastructure that supports all modern technologies. The difficulty in managing the timing and quality of such technical infrastructure increases with growing dependence on global R&D networks, as the number and complexity of market interfaces increases dramatically. As a result, the quality and availability across a research network of qualified science and engineering data, standardized measurement and test methods, an IT infrastructure, etc. are critical attributes of efficiency. That is, investment in supporting infratechnologies and standards must proceed in concert with investment in proof-of-concept research and subsequent applied R&D.

While potentially more efficient, an important attribute of global networks for domestic economic growth policy is the fact that the value added from the R&D and subsequent

[38] One can ask why do not existing domestic supply chains remain in place, especially with the increased need for collaboration due to backward distribution of R&D. As explained in the sections on technology life cycles, a particular tier can move offshore in a sequence of steps (first manufacturing and then R&D), especially as a technology matures. Once established in a another economy, more attractive investment incentives and superior overall innovation infrastructure in that economy can lead to indigenous tiers evolving above and/or below the original transplanted tier (for example, the emergence of semiconductor design firms in Taiwan after the establishment of chip manufacturing capability).

manufacturing and derived services is also going to be distributed across countries. Thus, economic growth strategies of the future must be sufficiently robust and efficient to draw global capital into the domestic economic economy. That is, a large enough share of the global value added from investment in the technology over its entire life cycle sufficient to attain domestic economic growth objectives is the critical policy impact metric.

Looking forward, nanotechnologies will drive future manufacturing innovation and process productivity. Developing these technologies will require major long-term R&D commitments by governments and their domestic industries. The innovation leaders will be the countries that develop entirely new methods allowing the manipulation and assembly of nanoscale components into nanodevices with complex functionality. Generic technologies will likely be available for licensing at attractive rates in the early phases of nanotechnology life cycles, but the value added in subsequent phases, where experience with process technologies feeds back into new R&D, will accrue to those economies that invest in both stages of economic activity (R&D and manufacturing). Staying competitive over the entire technology life cycle is essential to maintain domestic value-added growth, including growth in employment.

Whatever the particular manufacturing technology, private investment does not take place in a vacuum. In particular, an elaborate economic infrastructure is required. In competitive economies, economic infrastructures facilitate (1) the financing of investments in advanced manufacturing technologies, (2) the conduct of advanced manufacturing R&D, (3) the integration of the results of R&D into production systems, and (4) the provision of skilled labor to effectively use both the equipment and associated software. Such infrastructures are difficult to construct and maintain. Economies with efficient R&D networks, venture capital markets, integrated supply chains (virtual or actual), and education and training facilities have competitive advantages that are not easily established—or imitated. Such ecosystems, often called technology clusters, are proliferating globally as the means for driving regional economic growth.[39]

The difficulty in managing the evolution of such ecosystems increases with growing dependence on multiple actors in R&D networks and associated manufacturing clusters, as the number and complexity of market interfaces increases dramatically. As a result, the quality and availability across a research network of qualified science and engineering data, standardized measurement and test methods, an IT infrastructure, etc. are critical attributes of efficiency. That is, investment in supporting infratechnologies and standards must proceed in concert with investment in proof-of-concept research and subsequent applied R&D. Darby and Zucker (2003) provide the example of polymerase chain reaction (PCR)—an infratechnology used to amplify the number of copies of a specific region of DNA. PCR facilitates the production of enough DNA to conduct experiments, run tests and so on. It has thereby enabled applications ranging from detection of infectious agents to forensic applications.

R&D policy for manufacturing must also recognize that traditional R&D funding strategies in which components are developed first and then "fitted" into the final manufacturing system are inefficient. In effect, productivity at the systems level is addressed after the hardware components are developed, which reduces the efficiency of systems integration. However, because system-level productivity ultimately contributes as much or

[39] See Zhang et al. (2009). Clusters promote more interactions among research institutions (universities and government laboratories), innovators, their suppliers, venture capitalists, and other public-sector infrastructure. Such clusters increase both cooperation and competition, resulting in a much more effective innovation ecosystem. They also increase the efficiency of R&D through localized knowledge spillovers.

more to manufacturing productivity as do the system components, it cannot be ignored. The cluster model, embodying joint strategic planning between industry and government, can efficiently manage the needed R&D as a portfolio, where the member technologies will comprise the eventual manufacturing system.

Finally, overall R&D efficiency also requires both public and private institutions that carry out their respective roles in an integrated and complementary manner. It is not a coincidence that the two winners of the 2009 Nobel prize in economics (Elinor Ostrom and Oliver Williamson) are institutional economists. However, unlike most Asian economies and some European economies, the United States (at least at the federal government level) has in the past failed to understand the importance or the complexity of the modern innovation economy.

A major barrier in this regard is the dominance of federal R&D funding by mission agencies (DoD, NIH, NASA, etc.). Mission agencies account for 91% of total federal R&D funding). The R&D portfolios of these agencies are optimized for their public missions. While their R&D funding stimulates technology development that has economic impact, the R&D portfolios are not directed at the economic-growth objective. For example, as pointed out in an NRC report, industry contributes only about 1% of DoE's funding. Other countries in both Europe and Asia stand out in stark contrast. Taiwan's major R&D agency, the Industrial Technology Research Institute (ITRI), has the single-purpose mission of technology development and commercialization. Taiwanese industry contributes about one-third of ITRI's budget. DoE generates 0.1 patent per million dollars of R&D compared to 2 patents per million dollars for ITRI. The NRC report also points out that the economic growth orientation of ITRI means that technology transfer is "a dedicated mission, whereas for DoE it was a supplementary mission, not one central to the [agency] management's intent" (National Research Council 2007, p. 33). This comparison is not a criticism of DoE. It is simply a fact that mission R&D agencies are not organized to emphasize technology development primarily for commercialization purposes.

14.5 The bottom line

For high-income economies, the more labor-intensive a technology, the more likely it is to be offshored. However, because more capital-intensive technologies employ less labor per unit of output, automation has been resisted by some politicians due to the initial negative impact on employment. Of course, without automation, all jobs in the particular industry will eventually be lost, so underinvestment in capital-intensive technologies is not an option, if one wishes domestic manufacturing to survive.

The correct policy perspective is that because automation reduces unit cost and potentially increases quality and flexibility, such a strategy will result in increased global sales, which, if significant, will increase employment as domestic shares of global markets expand. However traditional automation, whose primary focus has been labor-content reduction, is no longer a sufficient investment strategy. Going forward, new technology-based strategies are needed that focus on flexibility and quality. For many manufacturing industries, the ability to produce one unit with a specific set of performance attributes as cheaply as 10,000 units implies a major quantum increase in technology in order to meet demand for customized products from a wide range of users.

A significant degree of "mass customization" at low cost essentially means that minimum efficient output levels have to be greatly reduced. Achieving such a goal, however, will require significant advances in multiple manufacturing process technologies.

Currently, truly customized products are available only for luxury goods, which are very expensive due to the high fixed costs relative to unit sales and the additional cost of some degree of customization.

In summary, three major requirements for competitiveness in manufacturing are (1) increased technological content of products, (2) more efficient and flexible production processes, and (3) greater use of information technology to a) manage computer-integrated manufacturing and b) more effectively integrate all business operations in manufacturing supply chains.

The policy conundrum was stated succinctly by Lawrence Summers, director of President Obama's National Economic Council:

> …if you want people to make 40-year investment decisions in a way that reflects your policy preferences, you better know what your policy preferences will be 10 years from now. How do you square that with the need for flexibility? I don't have all of the answers here, but I'm pretty sure that saying we should just let the market rip is not a viable strategy and I'm pretty sure that commandeering the whole thing by government is not a very viable strategy either.[40]

The answers to this challenge are

(1) Initiate R&D programs based on systematic strategic planning that identifies new technology trajectories early and then implement institutions to manage them in the same way a mutual fund is managed—as a portfolio where the objective is to maximize the long-term rate of return on the portfolio at the technology system level. This approach means that (a) the long-term needs can be more effectively achieved through a focus on the manufacturing system technology, which changes relatively slowly, and (b) the substantial risk associated with investment in new technologies can minimized through sound management of a diversified portfolio. Such management includes the expectation that individual R&D projects will fail and be terminated, while still achieving the target rate of return for the portfolio as a whole. This is not "picking winners and losers." Rather, the portfolio is targeted toward proofs of concept, which then allow industry to apply conventional RoI criteria to decide what directions will be pursued for applied R&D aimed at innovations.

(2) Understand the investment incentives for the elements of an industrial technology and the requirements for adjusting investment polices as the public-good content of these elements changes over a technology's life cycle; that is, do the economic analysis to effectively match policy response with the type of market failure in a dynamic context.

15 R&D policy implications

To achieve long-term superiority in the rapidly expanding technology-based global economy, the previous analysis suggests three major policy objectives:

[40] *Lawrence Summers, talk to the National Academy of Sciences' Science, Technology, and Economic Policy (STEP) Board, October 2008.*

(1) Increase the average R&D intensity of the domestic manufacturing sector to 6% through an improved R&D tax incentive structure. This approximate 50% increase would still be below the R&D intensities of semiconductors, computers, communications equipment, scientific and measurement instruments, pharmaceuticals, and a number of high-tech service industries, but it would enable the breadth and depth of innovation to increase significantly across the entire sector.
(2) Adjust the composition of national R&D to emphasis more long-term, breakthrough research. This will require a reversal of the long-term decline in government R&D funding relative to GDP and the establishment of an innovation policy infrastructure within the federal government to conduct underinvestment analyses, manage the portfolio of funded research, and support demonstration projects and technology transfer channels.
(3) Improve the efficiency of R&D performance and subsequent technology diffusion by increasing promotion of science parks and regional technology clusters and use of research portfolio and stakeholder management techniques.

However, even if the shortfall in R&D funding and the inadequacies of funding strategies and mechanisms were to be accepted, it is not clear that government science, technology, innovation and diffusion policies (STID) policies can be effectively selected and structured, given the lack of an accurate consensus growth model and an analytically-based policy infrastructure to apply such a model.

Policy instruments are of three types (1) tax-based incentives, (2) direct financial incentives, and (3) provision of technical infrastructure that increases the productivity of R&D and production. Current policy development and management infrastructures have inadequate understanding of the economic conditions that determine the selection of one instrument over others.

The choice of specific policy options depends on the nature of the underinvestment, which varies over a technology's life cycle. For example, a tax credit can be effective at increasing the amount of R&D spending by industry. That is, a tax credit will provide an incentive to industry to invest in more of the same type of R&D it is already doing and is therefore particularly useful in the latter phases of a technology's life cycle when market size and diversity of product R&D are expanding. However, it is less effective at adjusting the composition of this R&D. In contrast, government funding is appropriate for funding the risk spike (the valley of death) and for infratechnologies, so its focus is therefore on the transition between life cycles and efficiency of all types of R&D (Tassey 2007a).

The following are examples of what an informed policy decision process might yield:

(1) *Promote increased private-sector R&D through a larger and restructured R&D tax credit*. The United States was the first to implement an R&D tax credit in 1981. Since then, virtually every country has done the same. However, many nations have made their credits considerably stronger (OECD calculates that the United States now ranks 17th in terms of effective impact). Meanwhile, the US tax credit has been "temporary" for 28 years and its structure has hardly been analyzed. In fact, the incremental form of the current "R&E" credit is inefficient and penalizes persistently innovative companies. It should be replaced by a level credit and its magnitude increased in order to make a significant contribution to a national goal of increasing R&D intensity (Tassey 2007b).
For example, the tax expenditure under the credit for all industries was $6.4B in 2005. Approximately 70% of this amount ($4.5 billion) was claimed by manufacturing firms. Given that the US manufacturing sector funded $142.6 billion of R&D in that

year, it is clear that the existing credit is not going to make a significant contribution toward achieving a meaningful increase in this sector's R&D spending. A 20% level credit would have meant a tax expenditure of approximately $29 billion in this year. Because the few econometric studies of the impact of the credit indicate roughly a dollar-for-dollar response in terms of industry spending, such an incentive should contribute one-half of the desired increase.

(2) *Increase federal R&D spending*. Economic studies have indicated that the complementary nature of government R&D has the effect of increasing the productivity of private R&D and thereby increasing the rate of industrial innovation. Thus, increasing government R&D is not a substitute for private-sector R&D investment, as claimed by proponents of the "crowding-out" point of view. As the public–private asset principle makes clear, government funding should be directed at the initial phase of technology development—proof-of-concept research—and at research to develop infratechnologies and associated technical infrastructure. The large technical and market risk facing companies with only basic science in hand creates the risk spike, which inhibits investment in radical innovations that jump start new technology life cycles. For the most part, risk spikes can no longer be overcome by private-sector funding alone.

(3) *Improve the efficiency of R&D, innovation, and technology utilization*. The contracting of global technology life cycles demands that new technology platforms be developed more rapidly so that innovation occurs first in the domestic economy. Spending enough on R&D and the right types of R&D are two traditional imperatives. Conducting R&D efficiently is a more recent third requirement for effective R&D policy. Countries around the world are experimenting with new technology cluster mechanisms to promote R&D portfolio management, collaborative research, technology transfer, entrepreneur training, and the availability of venture capital. The economies of scale and scope enabled by such institutional structures are essential to compete in a global economy of shrinking technology life cycles and hence windows of opportunity for domestic industries.

(4) *Establish an innovation policy infrastructure*. The United States is the only major industrialized nation without an institutionalized science, technology, innovation, and diffusion (STID) policy development and management infrastructure. It is impossible for government to support new commercial technologies in the necessary time frames associated with life-cycle evolution without systematic analyses of technological opportunities and the underinvestment phenomena that characterize their development and commercialization. This is especially true for broad and complex systems technologies like manufacturing. Concepts, such as a National Innovation Foundation, proposed jointly in 2008 by the Brookings Institution and the Information Technology and Innovation Foundation (ITIF), have received little attention from the policy arena, but an institutional structure of this type is essential.

In summary, 77% of US manufacturing executives surveyed by Deloitte Research and the Manufacturing Institute said the US needs a strategic approach to developing a manufacturing base (Engardio 2009). For such a "strategic approach" to be successful, the economic rationales described in previous sections must be implemented through policies that are built on a new innovation economics, reflecting the complexity of multi-element technology-based economic growth.

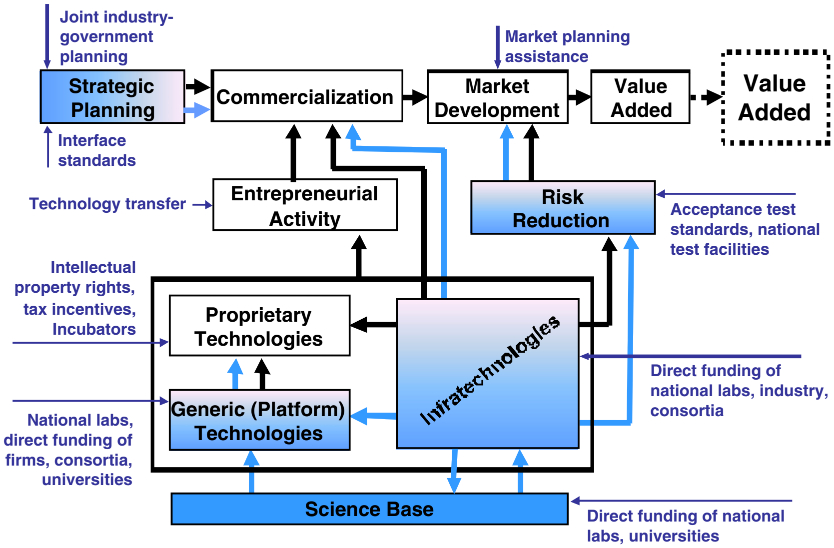


Fig. 10 Targets for science, technology, innovation and diffusion (STID) policy. *Source*: Tassey (2007a)

16 The complete manufacturing policy model

The major focus of this paper has been on rationales and mechanisms for improving the amount, type and efficiency of R&D directed toward new manufacturing technology systems. Focusing on R&D strategies is essential because (1) R&D is the investment that creates new, productivity-enhancing technologies, (2) R&D capability is essential for monitoring, selecting and assimilating technologies from external sources, and (3) without adequate investment strategies, modifications to other areas of technology-based growth policy will have little effect.

However, as pointed out in the discussion of technology life cycles, restoring the US economy to a position of product-innovation leadership can only be the first step in a successful technology-based growth strategy. Initial innovations are imitated, broadened, and improved upon as the markets for the new products grow. Larger markets provide incentives to invest in new process technologies and to differentially target additional groups of consumers. Scale and scope economies increase productivity and diversify markets based on the original set of innovations. Such economic activity is complex and subject to significant underinvestment across a wide range of economic asset categories.

In this regard, Fig. 10 shows how the multi-element model can be used to more accurately identify specific types of underinvestment across the entire technology-based spectrum of economic activity, as discussed in this paper, and match these phenomena with the most efficient policy responses.

This model is relevant for managing both maximization of domestic valued added within technology life cycles and the always difficult transitions between life cycles. The new science-driven technologies—biotechnology and nanotechnology—will be globally competed and the winners will be the economies that adopt new innovation ecosystems driven by complete and accurate policy models.

As Seneca, the Roman philosopher, put it, "If one does not know to which port one is sailing, no wind is favorable." That is, if one uses the wrong economic growth models and does not recognize the complex and integrated character of modern technology systems, then no amount of effort will succeed.

The United States does not have the correct growth model, which is why manufacturing sector policy continues to languish. Arguments that the domestic economy can prosper in the long run by specializing in services ignores both the co-location synergies with manufacturing and the fact that other economies are now aggressively integrating forward into high-tech services. That is, diversification will be an important attribute of successful economies going forward. Further, co-location synergies are real and are particularly important during the early phases of a technology's life cycle. Thus, US corporate strategies centered on design only or design plus services, while having worked for some companies, did so largely because the US market (i.e., the American consumer) has been dominant in the global economy and, until recently, because such strategies benefited from co-location with superior domestic high-tech manufacturing.

The era of the one-country technology-based growth model and denial of modern technology's complexity is over. Recognition of this fact and proper policy adjustments are essential for future competitiveness. The process of convergence is underway in services just as it has evolved in manufacturing. So, the policy questions are where is high-margin, high-value-added economic growth going to come from in the future and how is it going to be attained?

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