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Beyond the business cycle: The need for a technology-based growth strategy

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This paper assesses the limitations of monetary and fiscal policies for establishing long-term growth trajectories and instead proposes a technology-based economic strategy targeted at long-term growth in productivity. The model expands the original Schumpeterian concept of technology as the long-term driver of economic growth where technology is characterized as a homogeneous entity developed and commercialized solely by industry. Instead, the new model defines technology as a multi-element asset that evolves over several phases of the R&D cycle, is developed by a public–private investment strategy, and is commercialized by a complex industry structure of both large and small firms. Eventually, the policy choice is between traditional macrostabilization policies that increase aggregate demand but do not significantly increase the real incomes of workers, resulting ultimately in inflation; or a technology-driven investment strategy that increases the productivity of the economy, thereby increasing the capacity of an economy to grow without inflation.

Keywords: economic growth policy; technology; innovation; Schumpeter; R&D; productivity.

1. Introduction

Like Albert Einstein who spent the last half of his life trying to develop a unified field theory, the US economy is locked in a seemingly perpetual search for a unified economic growth model. The importance of this search has been accentuated by the persistent weak performance of the US economy following the 2008–9 recession, which has created growing concerns regarding the ability to return to acceptable long-term rates of growth. These concerns have been expressed largely in the form of a debate over the right combination of monetary and fiscal policies to apply. This focus is the result of the persistence of traditional domestic economic growth policies, the core of which consists of these policies.

However, such 'macrostabilization' (monetary and fiscal) policies have strong limitations with respect to stimulating long-term economic growth. This fact creates the need for a shift to greater emphasis on microeconomic growth policy—an imperative that has reached crisis proportions in many industrialized nations due to decades-long underinvestment in productivity-enhancing assets, especially technology.

The level of consternation over sluggish growth has been particularly high in the USA because in the decades following World War II, this country benefited from a structurally superior economy, characterized by the accumulation of a set of economic assets that drove high rates of productivity growth. This fact enabled macrostabilization policies to be used successfully to maintain an environment sufficient to attain acceptable long-term growth rates.

Such policies—derived from monetary and fiscal (Keynesian) economics—rely on stimulating a combination of investment and consumption until the economy attains 'escape velocity'; i.e. rates of consumption and investment by the private sector that can maintain acceptable and sustainable rates of economic growth. These macrostabilization policies are implemented to help manage implementations of the so-called neoclassical model of economic growth.

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However, US domestic investment patterns have deteriorated over several decades, especially relative to an increasing number of industrialized nations. The result has been increasingly negative trends in key economic indicators such as the trade balance and household income. The neoclassical growth model predicts that such trends will not happen due to self-correcting market mechanisms, but they are persisting nevertheless.[1] As the situation became worse, an explosion of public and private debt ensued as an unfortunate attempt to maintain standards of living in the face of rapid growth in the productivities of other nations' economies that increasingly pulled jobs out of the USA.

This situation demands a new growth paradigm based on a greater reliance on investment across a wide range of assets. The 'range of assets' is a critical dimension of the proposed growth paradigm, as this portfolio distinguishes what are called 'neo-Schumpeterian' from traditional neoclassical growth philosophies. This distinction is absolutely essential to understand, as growth policies based on the latter school of thought are increasingly ineffective.

In the neo-Schumpeterian realm, the core of a 'national economic strategy' is a sustained, high rate of productivity growth. Yet, this central role of productivity is still questioned by some, who argue that the increase in output per unit of labor reduces employment. The opposite is the case. Even though productivity growth typically reduces the labor content of a unit of output, the resulting combination of improved product and price performance yields larger market shares. This, in turn, creates a demand not only for additional workers but also for higher skilled and thus higher paid ones in order to produce the more technically sophisticated products enabled by the higher productivity and demanded by today's consumers. The cost of inadequate productivity growth is seen clearly in a number of economies in the form of falling relative incomes.[2]

Economic studies show that advances in technology are the only source of permanent increases in productivity (Basu et al. 2001). In contrast, technologically stagnant sectors experience slow productivity growth and, therefore, above average cost and price increases. Rising prices increase these sectors' measured share of nominal gross domestic product (GDP), thereby lowering average productivity growth for the entire economy (Baumol 1967; Nordhaus 2006).

In essence, the long-term growth paradigm can be viewed as driven by a set of fiscal policies, but these policies must be investment oriented and transcend many business cycles. In contrast to stabilization policies, the emphasis must be on investment in a range of productivity-enhancing technologies. Fiscal policies have a modest investment component, but typically, focus largely on conventional economic infrastructure such as transportation networks. While such 'shovel-ready' investment projects are having a positive impact and are essential for an economy with a deteriorated traditional economic infrastructure, their scope and magnitude is inadequate for a long-term growth strategy.

Equally important, such a strategy must be based on a growth model that reflects the increasingly complex and technology-intensive nature of global competition. The development and utilization of technologies on a scale large enough to attain significant global market shares for domestic industries require investment in a number of other categories of assets. These include: human capital, better channels for technical and business knowledge diffusion to firms of all sizes, incentives for capital formation, intellectual property protection, and modern industry structure (i.e. co-located and functionally integrated supply chains). These assets form the foundation of a broad ecosystem that functionally integrates R&D, capital formation, business management, and skilled labor. The emerging innovation ecosystem is a far more complex and integrated set of industries, universities, and government institutions than that which characterized the Industrial Revolution. This model is emerging on a global basis and thus a domestic economy-wide response is imperative.

2. Structural problems should be the focus of economic growth policy

As indicated above, a technology-driven and productivity-enhancing investment strategy is essential to enable the US economy, or any high-income economy, to compete successfully over time against other technology-based economies. Unfortunately, the USA has, for several decades now, failed to invest adequately in its economic future, with the result that its adaptive efficiency has declined.

2.1 Long-term vs. short-term growth strategies

A critical requirement for achieving acceptable rates of economic growth is that business-cycle fluctuations and the capacity for high long-term growth rates be managed by very different policy instruments. Fluctuations in economic activity always occur along a long-run growth trajectory (see Fig. 1). The dashed lines represent these short-run oscillations resulting from imbalances in the business cycle. The oscillations about the trend are managed by a combination of interest rates or monetary base control (monetary policy) and tax rates or government spending (fiscal policy).

The solid straight lines represent different growth trajectories. Their relative slopes (growth rates) are determined by long-term investment strategies that result in unique portfolios of economic assets.

A sound economic structure actually facilitates the job of stabilization policies by enabling more efficient

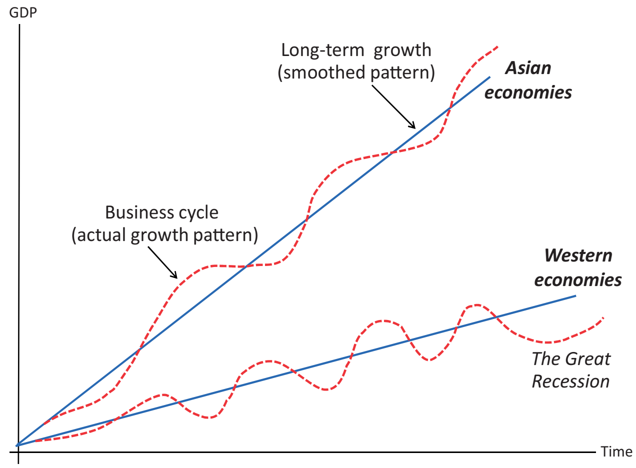

Figure 1. Long-term vs. short-term growth trends.

investment and productivity responses in recessions and a lesser tendency toward inflation in expansion phases. This has been evident during the last decade in Asian economies, where many nations have seen high sustained rates of growth and relatively subdued business cycles, as exemplified by the top growth trajectory in Fig. 1.

During the last ten years, the US growth trend has resembled the bottom growth path and has been a manifestation of a much longer investment deficit. This substantial drop in the rate of economic growth had a pronounced negative impact on tax revenue, which was exacerbated by lower tax rates and higher government spending on everything from wars to health services. The result was large budget deficits appearing almost instantaneously.

2.2 Failure to adapt

The US economy boomed in the 1990s, not because of tax rates (which were higher than in the 2000s), but because years of investment in the development and assimilation of information technology (IT) by both government and industry finally paid off in the form of accelerated productivity growth.[3] The message is that the modern economy cannot grow over time simply by stimulating demand.

Yet, influential economists continue to deny this fundamental problem. The broader policy debate has largely ignored those who argue for major structural reforms in education, investment in technology, more efficient industry structures, and government–industry partnerships, claiming instead that all the economy needs is more demand stimulation, specifically government spending.[4]

The movement toward unbalanced growth strategies in Europe and the USA is a response to globalization. The process of globalization began rather innocently in the 1970s and early 1980s, with a number of industrialized countries outsourcing low paying manufacturing and service jobs to poorer but aggressive Asian economies.

However, in the mid-1980s, the Japanese economy demonstrated the ability to acquire advanced product technologies from Western economies and combine them with its own improvements in process technologies. With modest differences, the Japanese growth model of the 1970s and 1980s has been adopted by other Asian economies over the past two decades. The result has been tremendous growth in the competitive capacity of China, India, Korea, and Taiwan. But the rapid ascendency of Asia has reduced rates of growth for most other industrialized countries. The macrostabilization policies implemented by Western economies have been based largely on debt accumulation in a furtive attempt to maintain current levels of consumption. These high debt burdens are now perpetuating slow long-term growth rates by inhibiting domestic investment by government.

Ignoring strucutural problems makes effective selection of long-term employment recovery strategies unlikely. These barriers have become increasingly more severe as globalization has gathered momentum. Fig. 2 shows that the average recovery in employment from the troughs of the first seven recessions after World War II reached a positive level after approximately four months, with employment growth then accelerating rapidly.[5] For three decades, this pattern held. Then, in the 1980s, significant technology-based competition began to emerge led by Japan. The subsequent 1990–1 recession showed the initial effects of globalization. A period of 16 months was required to reach a positive employment level relative to the recession trough.

The situation deteriorated further in the 1990s, as the impacts of globalization deepened. Those impacts were offset temporarily by a short-term burst in productivity growth from several prior decades of investment in IT. However, as the benefits of IT diffused globally, competitive positions were once again based on who produced the best products and services relative to cost. The US economy fell behind in a wide range of industries. This decline is evidenced by the fact that employment relative to the trough of the 2001 recession did not reach a positive level for 30 months. This was nearly twice the 1990–1 recovery time and seven times the average post-World War II recession recovery time. With respect to the 'recovery' from the Great Recession, 21 months were required for employment to exceed the level at the National Bureau of Economic Research (NBER) trough and has only slowly risen since—a meager return on historic economic stimulus.

In addition to job losses, globalization has also impacted the distribution of value added between workers and corporations. After World War II, the dominant position of the US economy, which resulted from high labor productivity, led to a rising share of GDP for American workers.[6] However, the advent of globalization in the 1980s started a reverse shift in that distribution from labor to industry, which continues today. This trend

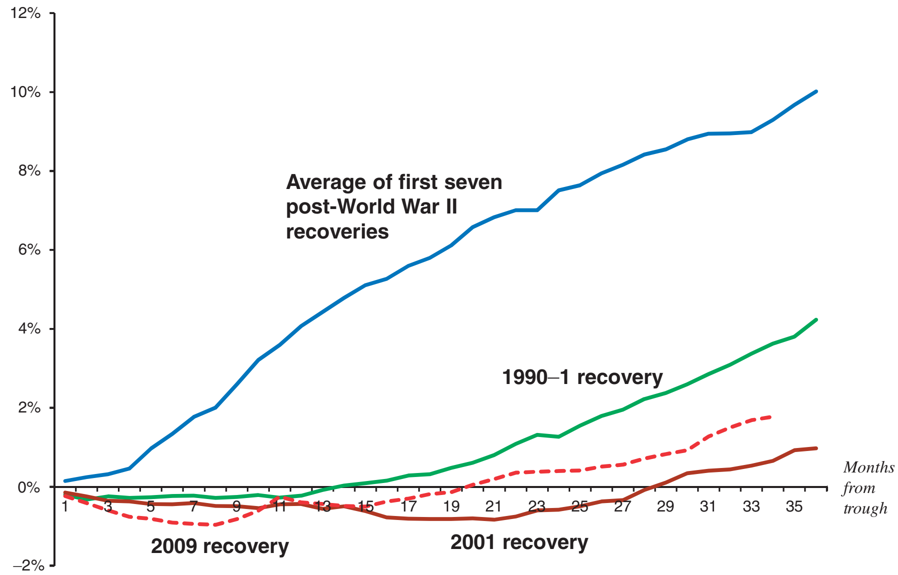

Figure 2. Non-farm employment growth in recession recoveries: Percent change from recession trough.
Sources: Tassey (2007, data updated); BLS for employment data <http://www.bls.gov/opub/ee/2012/ces/ces_new.htm> accessed December 2012; NBER for recession trough dates <http://www.nber.org/cycles/cyclesmain.html> accessed December 2012.

reversal occurred because US companies began reallocating labor to other economies where the same skill levels could be obtained for lower wages and where the host governments were increasingly able and willing to provide technical infrastructure support and other important incentives such as a lower cost of physical capital. Overall, the failure to increase US domestic labor's skills and the decline of unionization have resulted in an increasingly larger share of value added going to corporations in the domestic economy.[7]

2.3 Underinvestment in workforce skills

In today's information-driven and highly complex economies, labor is much more heterogeneous than was the case in the Industrial Revolution and hence substitution is more limited, not only across industries but also within industries. This heterogeneity has increased the potential for skill gaps in the labor force. One survey of skilled worker availability found that 32% of manufacturing companies were experiencing moderate to serious shortages in the availability of qualified workers, with certain sectors, such as aerospace/defense and life sciences/medical devices, reporting much higher levels of worker shortages.[8]

Yet, while these indicators imply the need for a crisis approach to education reform and much more investment in worker retraining, the response so far has been highly inadequate. According to the College Board, the USA once led the world in the percentage of 25–34-year-olds with college degrees, but it now ranks 12th among 36 developed nations. And, according to the testing organization, ACT, fewer than 25% of 2010 high-school graduates who took the ACT college entrance exam demonstrated the skills necessary to pass entry-level college courses. Similarly, based on Scholastic Aptitude Test (SAT) reading tests given to the class of 2012, the College Board concluded that 57% did not score high enough to indicate likely success in college.

More broadly, the entire school system is inadequate for today's modern technology-based economy. More incentives for students to choose science and engineering are needed and a much broader education and training infrastructure has to be developed to expand the skilled workforce. K-12 might have to become K-14 to truly upgrade US workers' skills, with the additional two years of education being community-college level training in specific technical (vocational) job categories, including subsidized apprenticeships with small high-tech firms who often cannot afford the overhead associated with bringing young workers up to adequate levels of productivity.[9]

The track to 'high-tech' vocational training must begin in high school to avoid the all-or-nothing decision now faced by American K-12 students: go to college, whether or not it suits the student or the needs of industry, or be relegated to low-paid trades, most of which are in declining manufacturing or service industries with little upward mobility potential. Finally, the school year must be lengthened. At 180 days, graduating US high-school students will have spent more than a full school year less in the classroom than the average for other countries; so, even if the quality of K-12 were competitive, American students would still be at a skills disadvantage.

2.4 Underinvestment in productivity-enhancing physical capital

Long-term underinvestment has been exacerbated for much of the past decade by a national savings rate that hovered around zero. This has meant that: first, virtually all investment was financed by foreign capital; and second, domestically stimulated growth was based on consumption. Neither provides a strong foundation for increasing productivity growth rates.

If policy-makers wanted to stimulate greater productivity in the domestic economy, one would expect a bias toward policies that leverage investments in the stocks of companies that either develop or use productivity-enhancing assets. General tax cuts were tried in the 2000s as a means of maintaining the growth rates of the 1990s. However, the modest resulting increase in consumption provided only a weak multiplier effect on corporate investment. Even when tax incentives are targeted at investment, the effect is to induce spending on the existing capital structure and thereby largely in the existing stock of technical knowledge. While capital formation is a critical element of economic growth policy, it is the technological content of available hardware and software that determines resulting productivity impacts.

Moreover, general tax expenditures for industry are small compared to other categories of tax breaks. A study by the US National Tax Foundation estimates that generally available tax provisions will cost US$54.8 billion in 2011. This amount is relatively modest compared to the sum of projected exclusions for employer-provided health insurance (US$177 billion), pensions and retirement programs (US$142 billion), the mortgage interest deduction (US$104 billion), and tax benefits for state and local governments such as the exclusion for bond income (US$92 billion).[10] Moreover, the current annual tax expenditure for the R&D tax credit, which helps enhance the productivity of physical capital, is only US$8.5 billion.

In contrast, investment in productivity growth offers the prospect of positive long-term returns. The reason is that superior productivity results in larger shares of global markets, which, in turn, increases the demand for domestic labor. The economic growth potential is huge as 95% of all consumers live outside the USA. Moreover, while American consumers have been the engine of global growth for several decades due to their disproportionately high incomes, they are unlikely to significantly increase consumption for the foreseeable future as households reduce their level of debt, thus reducing domestic consumption as a source of growth. They will also suffer real income stagnation as competing economies' productivity growth rates exceed those in the USA.

The implication is that the US investment strategy must be designed to compete for global customers and must therefore be export oriented. Moreover, long-term productivity growth requires increasing the technological content of products, processes, and services. Technology investments demand higher skill levels, so that rates of compensation for the labor force will also rise over time.

3. The technology investment option

The ultimate objectives of economic growth policy are to create jobs and to increase per capita income. With respect to employment, recent analysis shows that with one exception, 'over rolling ten-year periods, employment and productivity growth have an almost perfect correlation'.[11] Moreover, decades of research have demonstrated beyond a doubt that technology drives long-term productivity growth and hence incomes. Bureau of Labor Statistics (BLS) data show that in all but one of 71 technology-oriented occupations, the median income exceeds the median for all occupations. Moreover, in 57 of these occupations, the median income is 50% or more above the overall industry median (Hecker 2005). The bottom line is that the high-income economy must be the high-tech economy.

The industries with high-skilled labor are also the industries investing in new technologies to combine with this labor. Thus, economic growth policy must place more emphasis on increasing multi-factor productivity, which is the driver of value added (profits plus wages and salaries). Achieving this goal requires coordinated advances in science, technology, innovation, and diffusion (STID) assets.

This strategy requires investments in multiple drivers: technology, education, capital formation, and industry infrastructure. Private-sector investment in hardware and software within the US economy ('fixed private investment') stagnated in the 2000s, which does not bode well for future productivity growth. Equally important, as described in the following sections, investment in the driver of the productivity of capital—technology—has also stagnated.[12] So, a policy imperative is to increase national R&D spending in order to increase the amount of technology available to be embodied in new productivity-enhancing capital stock.

However, the single most important policy problem is the fact that R&D is not a homogeneous investment, as assumed by neoclassical economic growth models and even by innovation economists. This complexity of the R&D cycle leads to confusion over the respective roles of government and industry. Therefore, as described below, R&D policy must be based on three critical drivers: the amount of R&D, the composition of R&D, and the efficiency by which the first two drivers are managed.

3.1 The amount of R&D investment

This has historically been the dominant R&D policy metric. However, due to the traditional neoclassical view of technology as a homogeneous private good, little policy analysis has been focused on the functional importance of public-sector technology research. The result has been a long-term decline in federal R&D spending relative to the size of the US economy and to the size of the federal budget.

The importance of the amount of investment in R&D with respect to its impact on innovation can for the first time be demonstrated using product and process innovation data recently compiled by the National Science Foundation (NSF) for a broad cross-section of industries. Fig. 3 compares an index of industry innovation (the sum of product and process innovations) with industry R&D intensity for 17 industries.[13] The index is created by adding the number of product and process innovations for each industry in the NSF database and plotting this index against industry R&D intensity. A positive correlation is clearly evident, underscoring the importance of R&D intensity as a major policy variable.

The vertical dashed line in Fig. 3 indicates the minimum ratio of R&D to sales that typically qualifies an industry as R&D intensive. 10 of the 17 industries fall below this minimum.[14] Over time, these industries will become increasingly less competitive and provide fewer jobs and lower rates of pay.

This positive relationship between R&D intensity and innovation is becoming increasingly important given that US$1.4 trillion is spent annually on R&D in the global economy—a huge level of investment, especially given the substantial leverage of resulting innovations on subsequent capital formation for production and subsequent marketing operations. In fact, economic studies have estimated the return on R&D to be four times the return on investment in physical capital, implying that R&D investment should be increased by approximately a factor of four (Jones and Williams 1998, 2000).[15]

This leverage on other categories of investment underscores the point that innovation is only the initial commercial application of a new technology. Over time, the majority of the economic benefits from investment in technologies are realized from scale-up and subsequent attainment of significant global market shares. In this regard, Table 1 provides a vivid demonstration of the importance of R&D intensity for manufacturing industries. The industries are segregated into high- and low-R&D-intensity groups for which the average rates of real-output growth are calculated for the periods 2000−7 and 2000–9. The difference in average growth rates between the two groups is remarkable.[16] Further, Table 1 provides a perspective on the relative effects of the 2008–9 recession on the two groups. While the downturn negatively affected several of the R&D-intensive industries, as a group their average grow rate remained effectively unchanged. In contrast, all of the non-R&D-intensive industries suffered significant declines in output growth when the recession is included. The major policy implication is that when decision-makers are looking for levers to stimulate output, job growth and worker incomes, especially over longer periods of time, high R&D intensity should be a primary target.

Manufacturing industries are important to long-term economic growth in an advanced economy, not only because worker incomes are higher than the average for all industries but also because the manufacturing sector has a disproportionately large share of domestic industry R&D (70%) and employs a disproportionately large share of R&D personnel (60%). Allowing this sector to move offshore would decimate the economy's R&D capacity and hence its overall innovation infrastructure. The problem is that the average R&D intensity for all US manufacturing is only 3.7%—well below the lower end of what are considered to be R&D-intensive industries

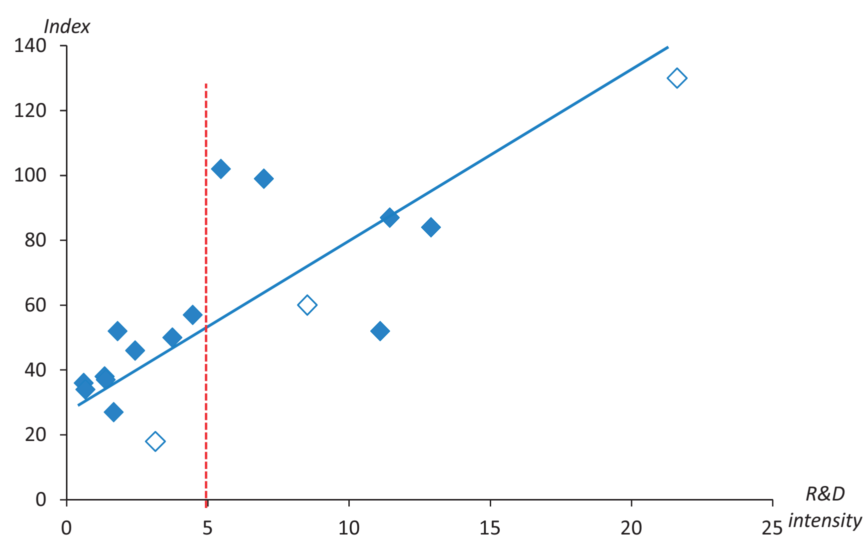

Figure 3. Rate of innovation vs. R&D intensity: percentage of companies in an industry reporting product/process innovations, 2003–7.
Index = sum of percentage of companies in an industry reporting product innovations and percentage reporting process innovations.
Sources: National Science Board (2010: Appendix Table 4-14; Boroush (2010).

Table 1. Relationship between R&D intensity and real output growth in manufacturing

Industry (NAICS Code)	Ave. R&D intensity, 1999–2007	% change in real output, 2000–7	% change in real output, 2000–9
R&D intensive:			
Pharmaceuticals (3254)	10.5	17.9	4.9
Semiconductors (3344)	10.1	17.0	1.1
Medical equipment (3391)	7.5	34.6	39.5
Computers (3341)	6.1	109.9	147.0
Communications equip (3342)	13.0	−40.0	−59.7
	Group ave: 9.5	**Group ave: 27.9**	**Group ave: 26.6**
Non-R&D intensive:			
Basic chemicals (3251)	2.2	25.6	−7.8
Machinery (333)	3.8	2.3	−22.4
Electrical equipment (335)	2.5	−13.4	−33.4
Plastics and rubber (326)	2.3	−5.2	−28.0
Fabricated metals (332)	1.4	2.6	−23.6
	Group ave: 2.5	**Group ave: 2.4**	**Group ave: −23.1**

Sources: NSF for R&D intensity (Science and Engineering Indicators 2012, Appendix Table 4–16) and BLS for real output (data provided by BLS staff). NAICS is the North American Classification System <www.census.gov/eos/www/naics> accessed December 2012.

and, surprisingly, unchanged from the 1980s. However, as the dramatic negative change in the growth rate of the communications equipment industry (NAICS 3342) demonstrates, even a high R&D intensity is no longer a sufficient condition for maintaining domestic production content. The high R&D intensity of this industry indicates that the remaining domestic economic activity is competitive. Unfortunately, it is also clear that other segments have been moved offshore, thereby reducing the domestic industry's share of the global industry's value added and consequently domestic jobs.

Decades of economic research have shown clearly that technology is the long-term driver of productivity growth. One would therefore think that technology investment would be the highest priority among the elements of an economic growth strategy. Yet, its role is hardly mentioned in current economic growth policy debates and, therefore, the migration to a new technology-based growth strategy is being stymied.

The result of this investment myopia is shown clearly in Fig. 4, which depicts long-term trends in US R&D intensity. The peak R&D intensity was reached in the mid-1960s and has not been exceeded in the subsequent 45 years, in spite of the relentless growth in R&D investment by other countries. The USA was once the most R&D-intensive economy in the world, but its ranking has steadily declined. As of 2009, OECD data show that the USA ranked ninth in R&D intensity.

The rapid expansion of national R&D spending in the early post-World War II period was driven to a significant extent by national security concerns, but the latter part of this uptrend was the result of a realization that the role of science and technology would expand rapidly in all segments of society. President Kennedy's 1961 speech calling on the country to greatly expand science and technology (S&T) investment was responded to for only a few short years (until the mid-1960s) and then largely forgotten.

OECD data reinforce how badly the USA is lagging its competitors in responding to growing technology-based competition. The US growth rate over the past 15 years—a time of rapid expansion of global R&D—has been one of the lowest among major industrialized nations. The 15% increase for the US economy compares to 24% for Japan, 29% for Germany, 50% for Korea, over 70% for Finland and Taiwan, 100% for Singapore, and 200% for China. A last place growth rate is not something an advanced economy can afford with the world's R&D spending continuing to expand rapidly. China's dramatic growth in R&D is coming off a low base of R&D intensity, but only apostles of denial will try to downplay its long-term significance, especially as it is a manifestation of a national plan to attain technological superiority across multiple industries. The USA still conducts more R&D than any other economy (as it should being the largest economy), but its slipping relative R&D intensity foretells a constrained rate of economic growth.

3.2 The composition of R&D investment

An accurate policy model for managing technology-based growth recognizes the several phases by which scientific knowledge is turned into successively more applied technical knowledge until the point of commercialization is reached. The earliest phase of technology research seeks to prove the concept of how the technology will eventually provide commercially viable products or processes. 'Proof-of-concept' technology research typically occurs a long time before commercialization. Its broad 'technology-platform' character provides the potential for multiple market applications; that is, the aggregate potential economic growth impact is substantial. However, the

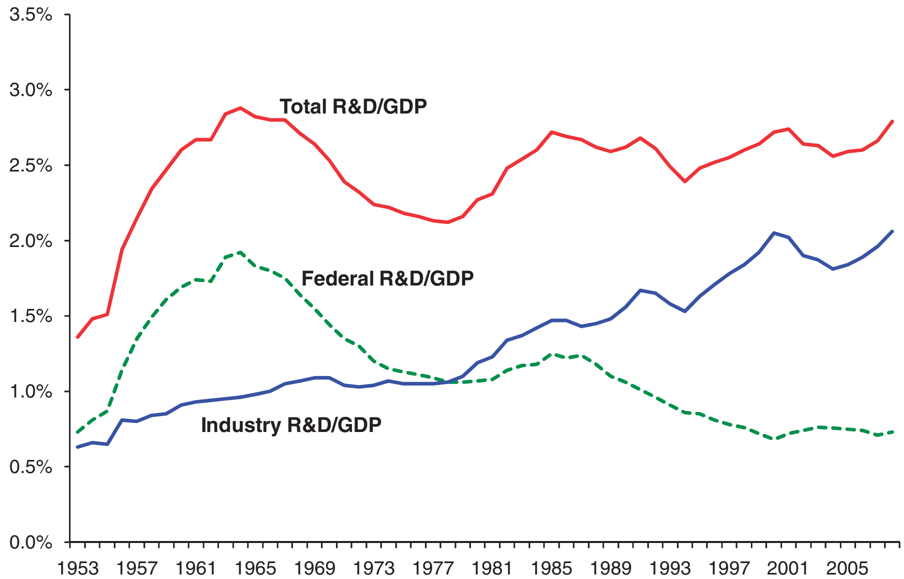

Figure 4. US R&D intensity: Funding as a share of GDP, 1953–2008.
Source: National Science Foundation *National Patterns of R&D Resources*, 2008 Update, TABLE 13. Gross domestic product and research and development (total, federally funded, nonfederal): 1953–2008.

higher discount rate applied by the private sector to adjust expected rates of return for time and also for both high technical and market risk combine to produce significant underinvestment by industry in this early-phase technology research. In addition, the broad sets of potential market applications (economies of scope) characteristic of modern generic technology platforms typically extend beyond the market foci of individual firms, thus further reducing the expected rate of return for a single company (Tassey 2007).

The consequent trend toward less investment by industry in radically new technologies with long-term and large economic impact potential is demonstrated in Fig. 5. Using 19 years of data on annual planned company R&D expenditures from surveys of its members by the Industrial Research Institute, the bar chart shows trends in two 'sea-change' indexes of R&D investment.[17] The light-shaded bars are the annual index numbers for 'new business projects'; that is, short-term R&D aimed at market applications within current technology life cycles. The dark bars are the annual index numbers for 'directed basic research'; that is, investment in longer-term, higher-risk R&D projects that will define future technology platforms and hence life cycles.

The trends in the two indexes are starkly different. Over almost two decades, US industry has regularly increased its investment in short-term R&D to respond to growing competitive challenges in the global economy, while regularly decreasing planned investments in the more radical research that provides the technology platforms for competing in future technology life cycles.

The Federal Government has not responded to this growing investment gap. As indicated in Fig. 4, the 50-year decline in the government's R&D spending relative to GDP shows no sign of abating. In fact, government R&D budgets are under threat of absolute declines from current levels. Even the long-term growth in industry's R&D intensity topped out in the last decade, as increasing portions of domestic company R&D funding are allocated to other economies. Yet, seldom in the interminable discussions in Western economies of what to do about inadequate rates of economic growth are these and other indicators of technology-based investment discussed.

In addition to its inadequate size, the Federal Government R&D budget has historically been focused on specific mandated missions (national defense, health, space exploration etc.) rather than on economic growth as a first-order objective.[18] In the past, many of the technologies resulting from mission-oriented research have spun off into significant additional commercial applications (that is, economies of scope were eventually realized from government-funded platform technologies).

This funding strategy worked well enough for several decades after World War II when the US economy dominated the world. However, the indirect path by which mission-oriented technologies are developed and then later spun off and modified to varying degrees to realize commercial applications draws out the R&D and hence the technology life cycles. This lengthy indirect process of realizing economies of scope from new technologies is no longer competitive in a world economy that conducts over a trillion US$ of R&D per year and is using increasingly efficient mechanisms for managing this investment. Such intense global competition is compressing all technology life cycles with the result that windows of opportunity are increasingly narrow. The severity of the R&D composition problem for the US economy is

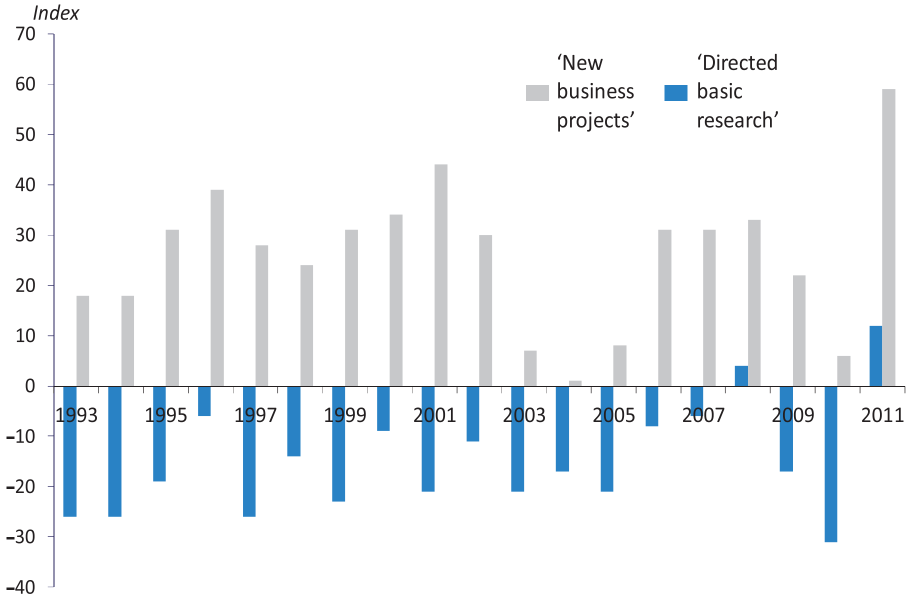

Figure 5. The 'valley of death' is getting wider. Trends in short-term vs. long-term US industry R&D, 1993–2011. Compiled from the Industrial Research Institute's annual surveys of member companies' R&D spending plans for the following year.
Note: sample size is not constant from year to year.
Source: Industrial Research Institute, *Research * Technology Management*, December issue, 1992–2010.

underscored by the fact that mission R&D spending comprises approximately 90% of the total federal R&D budget.

Government, with a lower discount rate, the ability to undertake riskier projects, and the resources to support a broad portfolio of long-term R&D must be a major supporter of the elements of complex modern technologies with public good content. Yet, as Fig. 4 demonstrates, government's capacity to contribute in the early part of the R&D cycle aimed at next generation technologies along with other types of technology infrastructure has steadily shrunk relative to the size of the economy and even more so relative to the size and importance of technology assets in today's global economy.

A considerable portion of government-funded R&D is performed by industry. Thus, if government R&D budgets had grown in concert with the economy' growth, the decline in industry's own funding of breakthrough research (see Fig. 5) could have been compensated for. Such research is critical to long-term rates of innovation because it focuses on the transition phase between basic research (which has no intrinsic commercial value) and development (which results directly in commercial applications). This transition phase (proof-of-concept research; also called the 'valley of death') plays the critical role of reducing technical and market risk sufficiently to encourage industry to invest the far larger funds required for applied research and then finally the development phase that creates innovations.[19]

Moreover, government funding for industry-performed (largely manufacturing) R&D is highly skewed with 75% going to two industries: instruments and aerospace (NAICS 3345 and 3364, respectively). Although receiving the dominant share of government funding for industrial R&D, these two industries account for only 19% of the value added produced by the high-tech portion of the US manufacturing sector and 10% of the value added from all of manufacturing.[20]

The trend in government applied research support is not reassuring in this regard. Federal Government funding for this phase of R&D has been unchanged in constant dollars for a full decade (since 2001). Other parts of the global economy recognize the need for government to help finance breakthrough technology research (for example, the EU's recently announced Seventh Framework Programme for Research and Technological Development is being funded at a record level of US$8.3 billion in 2011). These funds are targeted at universities, research organizations, and private industry (including small and medium-sized firms) to leverage the development of new technology platforms and eventually new industries.

An important characteristic of technology development and subsequent innovation is that the amounts of R&D spending increase as the research becomes more applied. US spending on development is approximately 3.5 times the amount spent on basic research and 1.7 times the amount spent on applied research. This leverage is normal, but the policy issue derives from the fact that industry hardly invests in basic research and is investing increasingly smaller portions of its overall R&D budget in proof-of-concept technology research. The reason is the difficulty for individual companies to project capturing adequate rates of returns on such long-term investments after adjusting for time, knowledge spillovers, and substantial technical and market risk.

3.3 The efficiency of R&D investment

R&D efficiency is increasingly important in a global economy with shrinking R&D cycle times. It is a composite of three factors:

- The portfolio of technologies which are pursued relative to the optimum one for maximum economic growth.
- The distribution of R&D funding across the phases of the R&D cycle relative to the distribution that minimizes R&D cycle time (time to innovation) and maximizes innovation output.
- The organization of R&D relative to the structure that optimizes the return-on-investment impacts from risk pooling and complementary public and private contributions. The latter (complementary-asset benefits) includes the mix of participants (universities, government, and industry), the mechanisms by which public and private actors collaborate (ecosystem attributes), and the effectiveness of the R&D infrastructure (research facilities, skills of researchers).

These attributes of R&D efficiency require a complex organizational format, which is rapidly evolving among the world's technology-based economies.

The single most important emerging organizational format, the 'regional innovation cluster,' has become a global phenomenon.[21] The cluster model offers an approach to increasing the efficiency of technology-based economic growth strategies through the regional co-location of public and private R&D assets. Co-location synergies among these assets increase the productivity of R&D and enhance risk pooling at the R&D stage and even during scale-up for production of new technologies. Moreover, the research consortium element of a cluster facilitates the effective management of intellectual property and its subsequent diffusion to commercialization entities.[22]

Clusters also provide concentrated labor pools with the relevant skills and promote technology diffusion and hence broader commercialization of research results. A fully functioning innovation cluster can facilitate management by the entire supply chain of successive technology life cycles through enhanced life-cycle investment coordination, including planning for and public–private funding of the transitions between life cycles.

The increasingly diffuse distribution of R&D in high-tech supply chains also requires more cooperation among multiple industries, universities and levels of government. Some clusters have built upon existing supply chain synergies in which suppliers and customers were already co-located and interacting regularly to cooperate on innovation. However, broad use of this policy instrument will require establishment of many new regional clusters, but 'natural agglomeration' of related industries (supply chain) can take a long time to occur. Therefore, a pro-active policy approach is required. Without such synergies realized through the application of public–private asset growth models, individual companies will find themselves competing not only against firms in other countries but also against those countries' governments that are partnering with their domestic industries.[23]

4. The new global competitive strategy

For a good portion of the post-World-War II period, the USA was the dominant technology-based economy. Virtually all technologies currently driving the world's economy originated in this country. R&D and technology assimilation efficiencies were not particularly important in the absence of significant foreign competition. Thus, individual companies and mission-oriented R&D agencies could operate independently. In spite of duplication, lack of economies of scope in R&D, and other inefficiencies, these agencies eventually produced technologies needed by their specific missions. Broader diffusion to the general economy occurred through inevitable but slowly developing spillover effects.

Today, however, growing global competition has shortened R&D cycles, requiring much more efficient technology funding strategies for both development and utilization. A major conceptual element of these new models is a characterization of the complementary roles of government and industry, especially in the early phases of a technology's development and in the provision of essential technical infrastructure (infratechnologies and associated standards). Thus, efficiency in both platform-technology and infratechnology development need significant upgrading.

Doing so requires growth models that include the major elements of an industrial technology, including the public-good components. However, in spite of overwhelming evidence from competing economies around the world, many Americans, including neoclassical economists, still argue that government involvement in technology development and utilization is 'picking winners and losers' or 'crowding out' private capital—implying a decision process that only the private sector is competent to undertake. In other words, no significant market failures are believed to exist in technology development and utilization, leading to the assertion that allocative efficiency is a purely private-sector activity.

Moreover, allocative efficiency is regarded largely as a short-term (within the technology life cycle) phenomenon. Longer term, the dynamics of global competition requires adaptive efficiency across life cycles, which in turn is based on government–industry partnerships derived from the public–private character of modern technologies and their supporting infrastructures. Once such a model is adopted, the 'picking winners and losers' argument disappears. Government co-funds the public-good portions of an emerging technology (technology-platform and infratechnology research) and industry funds the rest, in particular, the actual innovation efforts—where companies compete against each other domestically, as well as internationally.

The new theme is that, in the modern global economy, governments are becoming as much competitors as are their domestic industries. Traditional economists, with their simplistic view of the economic role of technology, object to this premise. The globalization of most large and, increasingly, medium companies means that corporate strategies are less dependent on the internal markets of any single country. As 95% of all consumers reside outside the USA, even US companies' strategic thrusts are aimed at the global marketplace. This trend increasingly leaves governments as the single major domestic economic agent that focuses entirely on the domestic economy and has domestic economic growth as its primary concern.

In summary, the indicators discussed in the previous sections—declining rates of growth in domestic fixed investment (hardware and software), R&D spending, workers' skills, and economic infrastructure (especially technical infrastructure) collectively convey a serious structural problem that weakens economic growth. Fear of change and lack of incentives to change plus a legacy effect of traditional economic growth models have combined to block adaptation to the globalization of the technology-based economy. Failure to adopt and fund the right growth model will mean substandard rates of productivity growth, resulting in restrained output, tax revenues, and real incomes—thereby perpetuating the existing economic malaise.

5. Managing the technology life cycle

An efficient economic growth policy is not just a matter of determining private- and public-sector roles in the context of a static market failure. The increasingly rapid pace of technological change requires dynamic policy support for the entire technology life cycle. The primary reason is that the nature of underinvestment by industry changes as technologies are created, mature, and finally become obsolete (Tassey 2013). The USA has lost enormous amounts of value added (and hence jobs) by ignoring the changing needs of domestic industries as their technologies and market opportunities evolve over time.

Once a new technology is initially commercialized, simultaneous scale-up of production capacity and product differentiation for multiple markets become critical issues. For the USA, scale-up is a significant barrier to long-term economic growth. This is because the vast majority of the economic benefits from new technologies results from the growth of their markets after they have first been introduced. Early and substantial investment in process technologies and the actual scaling up of optimized production capacity are essential to attaining large market shares in the increasingly technology-based global economy. Supporting this stage of economic activity requires a different mix of policy mechanisms compared to those required for the R&D stage.

A 2010 National Institute of Standards and Technology (NIST) study concluded that:

> U.S. leadership in invention has not been coupled with manufacturing success. Across a number of technologies—such as energy storage, power generation, and robotics—key invention and discovery have taken place within the US innovation system, but manufacturing has moved offshore. (Ralston 2010)

Former Intel CEO, Andy Grove (2010), stated that:

> Scaling isn't easy. The investments required are much higher than in the invention phase. And funds need to be committed early, when not much is known about the potential market.

Thus, setting aside the issue of the adequacy of US R&D investment, the US economy needs to augment its traditional focus on research that produces inventions and subsequent product innovations by increasing emphasis on the research needed to develop manufacturing processes capable of producing products that meet the quality and performance requirements of the global marketplace and yet also meet the cost targets needed for successful market penetration.

This problem is complicated by the fact that the US$1.4 trillion currently being spent on R&D across the global economy by countries competing in a growing number of markets is resulting in highly differentiated demand and supply within product categories. The resulting pressure to at least semi-customize applications of generic product technologies is a fundamental change from the Industrial Revolution, where conditions for success were dominated by the imperative to achieve economies of scale. That is, markets in the past were driven by the need to produce large quantities of homogeneous products at low cost. This central tenet of economic growth required companies to become large enough to maintain capital structures sufficient to attain the desired economies of scale.

However, today scaling is becoming much more complex. Manufacturing processes must increasingly be flexible in order to achieve the economies of scope required to serve a heterogeneous set of sub-markets with the same generic production system. Doing so requires flexibility while maintaining low unit cost, which can only be achieved through new processing techniques, massive use of IT, and a highly skilled and heterogeneous labor force. The forthcoming 'smart revolution' will attain this 'mass customization' objective at least in the countries that make the required investments.

Thus, while scale-up—the process of achieving a minimum efficient scale of production—is still essential, the key attribute of advanced manufacturing will be the ability to achieve this minimum scale at low output rates and do so for a range of differentiated products. This is a massive systems problem and will require increased funding of process R&D, manufacturing engineering education, and technical infrastructure that supports integrating process technology components into highly flexible manufacturing systems. More than ever before, productivity at the systems level will be a determining factor in future competitive success.

In addition, emerging technologies such as 3-D printing (additive manufacturing) will significantly alter the structure of the manufacturing sector's supply chains, in effect allowing raw materials to be configured into a final product in one step.

At the same time, the era of control of global technology-based markets by a single economy is over. No one country, including the USA, will dominate a major technology again. The 'next big thing'—nanotechnology—will be the first major technology in the last 60 years for which the USA is not guaranteed to be the prime mover. A number of countries in Europe and Asia have major research programs and their collective R&D investment is considerably greater than US expenditures. While current assessments put the USA ahead in nanotechnology development, this is small comfort because it is the initial part of the technology life cycle (early technology development and innovation) in which American expertise is still competitive.

Perhaps the most challenging of all aspects of technology-based competition is the transition from the current to the next technology life cycle. Failure to plan for and efficiently execute life-cycle transitions in highly competitive global markets with shorter windows of opportunity can bring down individual firms, industries, and even economies, as cycle management failures tend to be pervasive within national economic systems.[24]

In addition, moving offshore can block compensating innovation in the domestic economy. Optoelectronics—an increasingly important industry because of the forthcoming migration of computers to photonics-based technologies—is in the process of making a transition from a discrete to an integrated technology format (a technology life-cycle transition). Monolithic integration has performance and cost advantages and could potentially be a growth industry for the USA.

However, at this early phase of its life cycle, the mature discrete technology can be produced more cheaply in Asia (Fuchs et al. 2011). This typical situation—the new technology having a lower performance–price ratio in the early phase of its life cycle—slows market penetration. Failure by US firms to accelerate the evolution of monolithic technology and scale-up for initial markets in spite of the stretch out in cost disadvantage, may allow competing companies in other economies to eventually commercialize the new technology earlier and gain first-mover advantages. The generic policy response should be the cooperative dimension of the previously described public–private asset growth model, which promotes better strategic planning and life-cycle management at the domestic industry level, including the timing and supply of the required research assets plus the risk capital required to accelerate R&D and scale-up.[25]

Corporate CEOs understand the complexity of the rapidly emerging global technology-based economy and the consequent need for more flexible and effective strategies. Such strategies go well beyond the frequent cry for more innovation and promotion of entrepreneurship that dominate US S&T policy debates. Corporations now pay considerable attention to their relationships with multiple high-tech industries that make up their increasingly integrated supply chains. These industries, composed of small and large firms, provide both complementary categories of innovation and scale-up capacity, which are needed to compete in the eventual high-volume end-use markets. The dynamics of these relationships have motivated analysts to develop concepts such as 'open innovation' (Chesbrough 2004) and 'user innovation' (Gault 2011). The bottom line is that the failure to invest in efficiently integrated supply-chain structures and supporting technology infrastructures will lead to slow market penetration in the early phase of the technology's life cycle and almost guarantee low market share in the middle portion of that cycle.

Historically, the policy response to the loss of global market shares has often been general (tax, procurement) subsidies to the existing domestic supply chain. In other cases, various forms of trade barriers are erected. Because of the stigma associated with traditional forms of protectionism, countries have turned to currency manipulation as a more subtle technique for adjusting the balance of trade in their favor. In 2010 and especially in 2011, many economies took steps to debase their currencies in an attempt to achieve more favorable trade positions. None of these actions are acceptable solutions. While they may delay the inevitable, they cannot overcome structural problems and, in fact, they allow the problems to worsen by removing motivation for the needed changes.

Equally discouraging, many economists still respond to cries for policy action with the neoclassical free trade argument. Free trade is admittedly the ideal format because it is theoretically the most efficient mechanism for the allocation of resources across global markets, thereby maximizing global welfare. By definition, all nations participating in free trade are 'competitive' in one or more industries—namely, the ones they migrate to after trade ensues (Alic 1987). Technically speaking, this is true even for economies that do not have an absolute advantage in any industry—hence, the economic concept of the law of comparative advantage.

However, this two-century-old view of trade requires the assumptions that technology is a relatively minor asset or that it changes slowly. In fact, most of this time period has been characterized by relatively minor roles for technology with relative prices across countries still largely determined by endowed assets (arable land, navigable water ways, minerals deposits etc.). The fact that these assets were available in at most slowly changing quantities facilitated the utilization of global resources in accordance with relative prices. That is, the traditional neoclassical focus on allocative efficiency through the market price mechanism was all that was needed to maximize global economic growth.

Hence, the historical pattern of trade is claimed by traditional economics to be determined largely by market dynamics, leading to the belief in a passive approach to trade by government except for assuring market access for its domestic industries. Even as manufacturing's share of world trade began to grow two centuries ago, technology life cycles were long enough to allow comparative advantages to last for extended periods.

The advent of technology as a major tradeable asset has radically changed the dynamics of trade among nations. What the centuries old law of comparative advantage does not take into account is the fact that the basis for trade, i.e. a set of comparative advantages, can no longer be expected to remain fixed for very long. Technological change regularly alters relative prices and hence the absolute advantages or disadvantages across technologies and the economies that use them. In fact, today most modern economic assets are created, resulting in continual shifts in comparative advantage among nations (Tassey 2007, 2010). And, while global economic welfare may be increased, the different levels of adaptive efficiency among the world's economies result in losers as well as winners (Samuelson 2004).

Traditional economists do not deny the role of technology. However, they continue to assert that as one industry moves offshore, US companies will somehow automatically shift to newer and higher value-added industries. Because this process of 'upward mobility' with respect to value-added was the norm for the US economy for several decades after World War II, the process by which it occurred was hardly questioned or studied. This level of ignorance was not damaging as long as the US economy was the dominant source of new technologies. Inefficient development and diffusion of technology still led to positive adjustments in comparative advantage because the process occurred largely within the domestic economy: that is, both the old and new technologies were domestically created and utilized.

Unfortunately, analysts and policy-makers still only poorly understand the increasingly complex processes by which technologies are created, assimilated into economic systems, and ultimately drive long-term productivity and income growth. In the absence of a well-conceived and articulated growth model around which a consensus can form, frustration with the slow economic recovery and the historically negative view of government policies have fueled the revival of past populist movements in the form of the Tea Party and libertarian economics in the form of the Austrian School. As in past major economic crises, these movements arise based on the view that the problem is government and the solution, therefore, is to reduce its presence in the domestic economy.

Such trends run counter to the evolving global model of technology-based economic growth. In fact, other economies, being envious of the US standard of living, have examined the technology-based economic growth process more closely and are progressively evolving public–private asset growth models. As a result, the current global trends in investment in the development and use of technology are exceeding those in the USA. The apostles of denial argue that the USA still leads other nations in total R&D expenditures, but the critical policy variable, as discussed earlier, is not the level of R&D but the ratio of R&D spending to GDP (R&D intensity). The USA is the world's largest economy, so it should do the most R&D—and, more and more, do it efficiently.

The broadest and hence most complex indicator is technology-based competitiveness. Success results only from managing entire technology life cycles. In this regard, a study by the Information Technology and Innovation Foundation created an index of attributes and then estimated the rate of change in this index for the 40 leading industrialized nations. The USA was ranked 40th out of 40 countries in terms of 'the rate of progress on innovation-based competitiveness in the last decade' (Atkinson and Andes 2009). To be successful, a nation must have all of these attributes under management.

In summary, the highest order economic growth problem is the long-term inadequacy of investments in five categories of productivity-enhancing assets:

- technology (intellectual capital)
- skilled labor (human capital)
- hardware and software (non-human capital)
- industry structure and behavior (organizational/marketing capital)
- technical infrastructure (public capital)

Increasing the demand for housing does have a multiplier effect on that industry's supply chain, but this effect pales compared to the leverage from investment in technology for hardware and software that drive productivity in many industries. Equally important, the jobs created by a technology-driven supply chain are much higher paying—but, they must be sustained over entire technology life cycles to significantly boost to the standard of living.

6. The wrong growth model

6.1 The black box model

With respect to the 'composition' and 'efficiency' dimensions of the R&D cycle, a major problem is the failure of US innovation policy to divest itself of the 'black box' model. This label refers to the outdated characterization of industrial technologies as homogeneous private goods, which implies little or no role for government. In contrast, innovation economics recognizes that reality is much more complex.

The USA has been the last among the world's technology-based economies to reject the black box model of the innovation process. As a result, while it continues to adequately fund and thereby lead the world in basic science, it has relied largely on private capital to produce market innovations directly from the resulting science base (e.g. biotechnology) or indirectly through spinoffs from mission agencies' R&D portfolios (e.g. electronics, materials, IT). These mission agencies have varying degrees of freedom to support portions of a technology's development that go well beyond the range of investment support allowed for biopharmaceuticals and the small portion of the federal budget (approximately 10%) that directly targets economic growth.

Mission-oriented R&D and subsequent scale-up create a relatively small set of modest-sized markets, with extensions (spinoffs) into much larger commercial markets typically experiencing significant delays. As the consumer of defense technologies, the US Department of Defense (DoD) is allowed to control the entire technology life cycle from R&D to production to commercialization (through it procurement of defense technologies). The US Department of Energy (DoE) subsidizes R&D, but only recently in the case of clean energy technologies has it attempted to subsidize scale-up for commercialization. In contrast, an attempt to emulate DoD's Defense Advanced Research Projects Agency (DARPA) and DoE's Advanced Research Projects Agency (ARPA-e) role of supporting early-phase technology research (the development of new technology platforms) was the creation of NIST's Advanced Technology Program (ATP) in 1988. However, ATP was relentlessly attacked by conservatives until the program was finally terminated.

This dichotomy within federal R&D policy results directly from the singular neoclassical emphasis on allocative efficiency: that is, private-sector capital accumulation in response to market pricing signals. For the USA or any other government to adopt a 'technology-element model' to replace the black box version requires acceptance of the 'quasi-public' good nature of several of these technology elements (Tassey 2005a, 2007). The existence of these public-good elements, in turn, implies that modern technology-based markets suffer many more market failures than neoclassical economists realize (Tassey 2004; Atkinson and Audretsch 2008).

The implications of multiple market failures for technology-based growth policy and thereby the growth potential of a modern economy are depicted in Fig. 6. The 'black box' is disaggregated into three technology

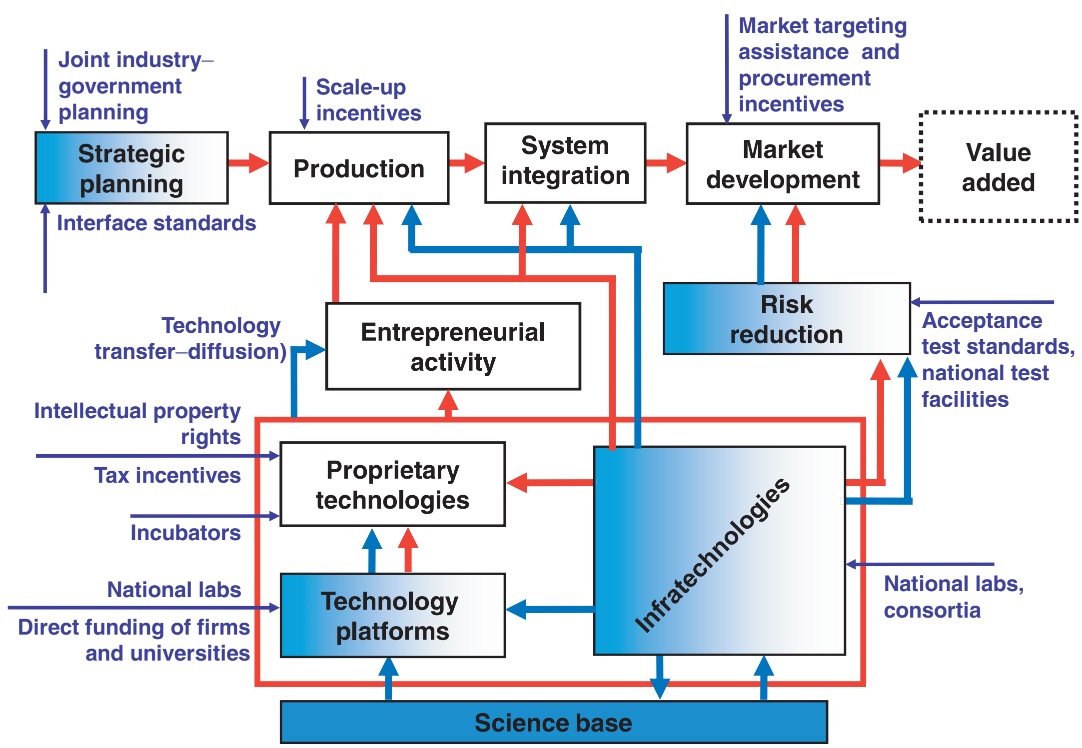

Figure 6. Managing the entire technology life cycle: Policy roles in response to market failures.

elements: new technology platforms (also 'proofs of concept' or 'generic technologies'), infratechnologies (and associated standards), and proprietary technologies that are the basis for innovations (the black boxes).

These three elements are not arbitrarily chosen.[26] They perform distinctly different roles in the development and commercialization of new technologies and they respond to distinctly different investment incentives. They are clearly visible within the organizational structure of high-tech companies. The existence of different investment incentives across these three elements means they exhibit distinctly different types and degrees of market failure. Public-good content and hence the degree of market failure is indicated by the shaded areas. The science box is fully shaded because it is close to a pure public good and therefore a dominant share of basic research is funded by government through universities. Proof-of-concept (technology-platform) research and infratechnology research are quasi-public goods, which means their development is co-funded by industry and government—hence the overall rationale for the partnership mechanism. Proprietary technologies are largely private goods, but associated excessive risk and/or time discounting can still lead to underinvestment. The policy point is that each of these technology elements, having different investment characteristics, exhibit different market failure patterns and therefore require different policy responses.

Corporations understand the correct technology-based growth model, which is demonstrated in their organizational structure and conduct of R&D: technology platforms are developed in central corporate research labs and the applied R&D (that results in proprietary technologies and ultimately innovations) is then farmed out to the R&D facilities in the company's line-of-business units. Many companies also have dedicated laboratories to assimilate/develop infratechnologies and associated standards (for example, analytical laboratories in chemical and biopharmaceutical companies and metrology labs in semiconductor companies). Thus, the technology element model (see Fig. 6) is derived directly from high-tech corporations' organizational structures.

The corporate application of this model worked fairly well when the USA was the dominant technological power. Large US corporations could apply lower discount rates to longer-term, higher-risk R&D projects because they faced relatively little competition and therefore long technology life cycles. The absence of significant competition also allowed projections of capturing multiple markets based on the new technology platform (i.e. achieving economies of scope). Finally, technological complexity was sufficiently low so that a single entity (a large R&D-intensive company) could be expected to have at least most of the R&D assets required to independently pursue major breakthroughs.

Today, however, virtually all high-tech companies are focusing more of their R&D spending on applied R&D in order to be competitive in the middle and later phases of technology life cycles, which now afford shorter windows of opportunity than in the past (see Fig. 5). Their central research laboratories are receiving a declining share of corporate R&D investment and an increasing portion of these laboratories' budgets is allocated to supporting their business units' applied R&D or assessing external sources of new technologies. Similarly, infratechnologies, which serve as the basis for industry standards, are themselves increasingly complex and often derive from a different science base than the industry's core technology. This complexity requires a significant investment by industry to support standardization, which is used by increasingly large numbers of firms. The result is significant 'free rider' investment disincentives for individual companies. Yet, standards are pervasive in high-tech industries and must be developed and implemented in a timely manner.[27]

Many economies are now compensating for these 'market failures' by establishing public–private research partnerships to pool risk, improve the efficiency of R&D, and diffuse new technology platforms more rapidly within domestic supply chains. These economies are also investing increasing amounts in the supporting technical infrastructure (infratechnologies and standards) to increase efficiency across the R&D, manufacturing, and commercialization stages of technology-based economic activity.

6.2 Co-location synergies

A second major conceptual problem is the failure of US policy to understand the importance of co-location synergies inherent in today's high-tech supply chains. At the sector level, claims by current economic thinking that an advanced economy can prosper solely as a service economy ignore the need for domestic sourcing of the large amounts of hardware and software needed by service firms. Short lead times for suppliers and the integration of new technologies into high-tech service systems require constant interaction between service companies and multiple tiers (industries) in the manufacturing supply chain. These interactions happen much more efficiently when these industries are geographically and institutionally close to one another.

Moreover, a majority of trade remains in products, not services, so the manufacturing sector is a serious growth policy issue. The US deficit in traded goods is five times the surplus in traded services. And, there is no guarantee that the US economy will maintain a trade surplus in services in the future. The bottom line is that US growth policies are not adapting to global competition, especially technology-based competition. 35 consecutive years of trade deficits for manufactured products cannot be explained by business cycles, currency shifts, trade barriers etc.

As stated succinctly by Pisano and Shih (2009):

> . . . restoring the ability of enterprises to develop and manufacture high-technology products in America is the only way the country can hope to pay down its enormous deficits and maintain, let alone raise, its citizens' standard of living.

Within the manufacturing sector, the high-tech portion of traded products, once viewed as the signature indicator of US economic superiority, fell into a negative balance in 1982 and that deficit continues to widen. This trend is partly the result of the weak R&D policy model described in the previous sections. Further, industrial growth policy is still focused on the industry, when supply-chain synergies clearly exist within the manufacturing sector. The backward movement of R&D from the original equipment manufacturers to supplier tiers (industries) in manufacturing supply chains greatly increases both the level and complexity of interactions among these tiers. By integrating electronics industries, Asian economies have taken over increasingly large shares of the value added in electronics products markets.

Finally, a critically important dimension of globalization is the fact that the typical technology life cycle is shrinking. However, the life cycle is not going to zero. Thus, policymakers who suggest that government funding of R&D is wasteful because the resulting technical knowledge spills over to competing economies are ignoring the essential dynamics of global competition; namely, the economy that innovates first and scales up the fastest will likely reap the largest share of the economic rewards because it is a distinct advantage to start out ahead of the competition over multiple life cycles, thereby repeatedly reaping monopoly profits and increasing returns to scale. Again, the imperative is R&D efficiency and rapid scale-up.

7. A neo-Schumpeterian growth model

Section 6 described elements of a growth model that is very different from the simplistic supply-side growth paradigm of neoclassical economics. A major difference is the recognition of the disruptive role of technology in the Schumpeterian tradition, as opposed to the traditional view of technological change as a slow, steady progression that is solely due to private investment as a competitive response to price changes.

The technology-element model also embraces the importance of competitive dynamics in determining comparative advantage among nations. However, unlike neoclassical economic growth theory, comparative advantage is determined by the relative efficiencies of public–private investment strategies. In fact, the increasing global scope of private industry's market strategies leaves government as the major differentiator of domestic competitiveness among nations through its public investment policies that determine the global flows of R&D and physical capital and the relative efficiencies of industry structures.

Modern technology-based competition requires two major modifications to Schumpeterian 'creative destruction'. First, the scope of potential market applications of today's technologies is much wider than in the 1930s and 1940s when Schumpeter wrote his incredibly insightful works. As a result, the market structures that develop and commercialize technologies are more varied. As pointed out by Audretsch and Link (2012), Schumpeter first emphasized the role of the entrepreneur and hence small firms as the engine of innovation. This focus resulted from the need for small firms to find a way to disrupt the established markets dominated by large firms. However, Schumpeter eventually reversed his view and emphasized the superior investment capabilities and market strength of large firms, which enabled them to be more efficient and successful innovators.

The major conceptual revision is recognition of the fact that both large and small firms co-exist in the same technology-intensive supply chain. Each supplies complementary assets and thus components of the ultimate technology systems. This complex industry structure is seen in the emergence of innovation clusters all over the world, where not just a single industry but firms of all sizes agglomerate into new supply chains that deliver new technologies through a much more distributed pattern of R&D and subsequent innovation than characterized the Schumpeterian industry structure.

Second, the complexity of modern technologies requires multiple mechanisms for their development and deployment. Increasingly, these mechanisms include various forms of cooperation not only among competing firms but more and more between government and industry. In fact, the role of government in the technology life cycle has become varied, ranging from the early phases of R&D where the public-good content is high to the transition from the R&D phase to scale-up for commercialization to the facilitation of market penetration by domestic firms through the provision of infratechnologies that become the basis for product acceptance testing standards. The latter is an example of technology infrastructure that is as important to today's technology-based economy as conventional economic infrastructure was to the industrial revolution. For example, sellers of advanced technology products and services must assure buyers that these complex products meet performance, quality, reliability, and interoperability specifications as well as meet government safety, environment, privacy, and security requirements. Without such technical infrastructure, technology-based markets cannot evolve.

In summary, Schumpeter's focus on the role of the large firm is understandable and, in fact, was a fairly accurate characterization of innovation economics until the last several decades. The current growth model increasingly evident across the global economy recognizes not only the complementary roles of large and small firms, but also the significant public-good content of technology platforms and the supporting infratechnologies and standards.

8. The policy imperative

To compete in a global technology-based economy, the three types of efficiency discussed in this paper must be achieved at levels sufficient to grow per capita income over time. The three types are not independent of each other. Allocative efficiency—the major focus of neoclassical economics—is necessary but not sufficient. This supply-side approach views efficiency in terms of the accumulation of a set of productive assets, which has a fixed maximum growth potential.

Whatever the pattern of asset accumulation dictated by relative prices, productive efficiency is also required. Its achievement is also traditionally viewed as an internal market problem. In a static growth model, productive efficiency is based on an underlying set of technologies, which determines a maximum potential efficiency level. New technologies raise this efficiency level, so the STID process is essential to understand and manage the adaptive investment process.

Traditional growth models allow for technological change and its effect on relative prices and hence the directions for capital accumulation, but the process is not specified other than to assume a vague sequence in which scientific knowledge is obtained from a source exogenous to the private economy and then somehow turned into new technologies, which are commercialized through private investment.

This situation was improved when Paul Romer (1990) explicitly included a 'knowledge production function' into the neoclassical general equilibrium growth model. He also identified the 'non-rival' and 'partially excludable' characteristics of technology that contribute to systematic market failure. Such underinvestment characteristics lead to the technology-element growth model discussed earlier, which requires a more complex knowledge production function (Tassey 2005b). Most important, it is the primary role of the technology-element model to specifically characterize the three major elements of industrial technology so as to facilitate the selection of policy instruments that can accurately deal with these and other factors that suppress private investment in technology (see Fig. 6).

Because technologies are created, used in economic activity, and then discarded when they become obsolete, the dynamics of managing the technology-based economy over time is an essential element of long-term economic growth policy. The complexity and evolutionary nature of modern technologies coupled with the increasingly intense global competition for technology-based markets make achieving adaptive efficiency difficult and require multiple roles of government in support of investment by domestic industries.

At a general level, US political leaders understand the imperative to invest in technology as the driver of long-term economic growth. Treasury Secretary Geithner has said that the USA should invest more in R&D.[28] In his January 2011 State-of-the-Union address, President Obama called for increased investment in R&D and innovation broadly to improve US competitiveness. Several weeks later, the White House issued a revised innovation strategy document directed at implementing President Obama's goals.[29] Federal Reserve Board Chairman, Ben Bernanke, stated that:

> . . . innovation and technological change are undoubtedly central to the growth process; over the past 200 years or so, innovation, technical advances, and investment in capital goods embodying new technologies have transformed economies around the world.[30]

Bernanke also points out that a growth rate in per capita GDP of 2.5% per year doubles average living standards in 28 years—about one generation—whereas per capita GDP growing at only one percentage point less (1.5% per year) leads to a doubling in average living standards in about 47 years—roughly two generations. The technology–productivity–growth paradigm is the driver of long-term increases in growth and hence in the standard of living.

Thus, the central theme of this paper is that the only way to achieve higher rates of long-term growth in per capita income is through sustained investment in productivity-enhancing assets and that technology is the core of the required investment portfolio. However, this general recognition of the growing role and importance of technology for competing effectively in the global economy has not resulted in a reversal of the long-term trend of underinvestment by the US economy. Over the past 50 years, US R&D intensity has remained flat and in the last decade fixed private investment (hardware and software) hardly grew. In contrast, many other countries have steadily increased their R&D spending relative to GDP and their overall rates of investment.

China has increased its R&D intensity by 199% over the past 15 years for which data are available. In December 2010, the Chinese government announced a plan to invest up to US$1.5 trillion over five years in strategic industries of the future (energy-saving and environmentally friendly technologies, biotechnology, new generation IT, advanced manufacturing, new materials, alternative-fuel cars). This huge sum amounts to about 5% of China's GDP and will be supplied by both government and industry. Even if this level of expenditure turns out to be too large for Chinese STID infrastructure to absorb in that period of time, it demonstrates a commitment to dramatically increasing the Chinese economy's innovation capacity. The Chinese five-year (2011–5) plan calls for 'cultivating and developing' these industries and the government plans to provide targeted tax incentives, including cutting the income tax rate in half for investors in the relevant technologies.[31]

The EU has shown an increased recognition of the need to systematically plan and manage technology life cycles to increase long-term rates of economic growth. Robert-Jan Smits, European Commission Director-General of Research and Innovation characterized Europe's new 'Innovation Union' strategy as the:

> . . . first time that Europe has implemented a counter-cyclical investment policy in support of research and innovation during an economic downturn.[32]

Europe has adopted an EU-wide R&D-intensity target of 3% by 2020.[33]

The US economic growth policy infrastructure needs to embrace the critical role of technology in response to several decades of economic research that shows it is the major long-term driver of productivity and income growth.[34] Government also must construct new policies addressing the scope of public and private economic assets that drive the evolution of high-tech supply chains.

However, even if the correct technology-based growth model were to be adopted, a major barrier to implementation remains. The complex set of technology-based assets required to achieve desired long-term rates of economic growth takes a relatively long time to accumulate, integrate, and achieve fully functional system status. Using regional innovation clusters as an example, Fig. 7 shows that the long-term desired impact of large increases in value added (more jobs and higher profits) can only be realized after a number of short-term and intermediate-term goals are achieved. Thus, policy-makers must not only understand the long-term nature of economic growth policy, but they must also track, measure, and report on short-term and intermediate-term indicators in order to maintain support and effectively manage the entire technology life cycle.

9. Conclusions

The global economy is experiencing unparalleled expansion, characterized by an enormous influx of new workers whose skills are increasing rapidly, leveraging the convergence of emerging economies with industrialized nations. This process of convergence has been repeated to varying degrees for centuries.[35] The difference this time is the collective breadth and size of the converging economies, whose workers are increasingly providing intense competition for labor in industrialized nations.

The policy response is to increase investment in productivity-enhancing assets, for this is the only way to increase global market shares and increase the standard of living over time. However, making an economy more technology intensive is a massive systems problem. The USA undertook the greatest technical systems challenge of all time by setting out to put a man on the moon in less than a decade. Similarly, restoring a competitive economic system based on technology development and commercialization will require substantial investment in a number of critical and interactive asset categories that comprise the emerging technology-based economic ecosystem.

All categories of economic assets—technology, labor, plant and equipment, organization and marketing, and a broad technical infrastructure to support all the other categories—will have to be upgraded. Because many of the world's economies have already adopted new technology-element growth models and are making substantial investments to implement them, the US response can be neither small nor inefficient. R&D spending, for example, must now be managed by the metrics defined earlier: amount, composition, and efficiency of conduct.

In terms of the amount of R&D, the major requirement is to upgrade the currently inadequate incentives for both

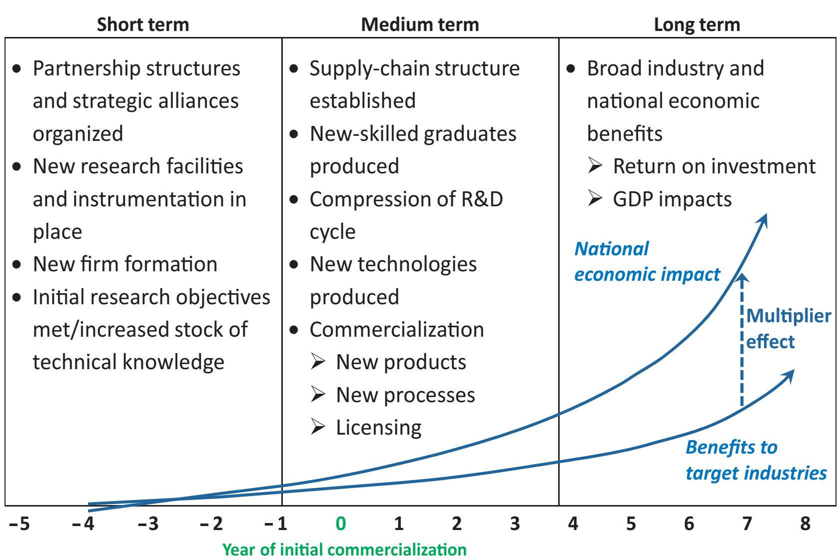

Figure 7. Timeline for economic impacts from STID policies: Accelerated economic growth through technology-based clusters.

US-based and foreign-based firms to locate R&D in the domestic economy by providing a competitive R&D tax incentive and an adequate supply of skilled R&D workers. R&D composition inefficiencies must be addressed by: first, reversing the Federal Government's declining spending relative to GDP (see Fig. 8); and second, creating a federal R&D policy that is holistic and driven by economic growth and is based on portfolio management techniques that ensure complete and efficient development of new technology platforms and supporting infratechnologies. Finally, efficient national R&D strategies will be dependent on new public–private research infrastructures in the form of regional technology-based clusters.

When a society decides to increase the portion of its government's budget allocated to developing new technologies, it happens. The Russian space program in the late 1950s was the wake-up call that elicited an immediate and broad response in terms of increased US Government R&D spending. This was motivated in part by President Kennedy's 1961 speech on the need to invest more in S&T. Kennedy recognized that the USA was being challenged technologically for the first time and that this pressure would grow and expand its scope in the years ahead. Unfortunately, the priority status for technology investment lasted for only a few years and then government R&D spending intensity went into a half-century of decline (see Fig. 8).

President Obama in his 2011 State-of-the-Union address repeatedly called for a return to innovation as the engine of US competitiveness. Since that speech, government policies aimed at reviving and expanding the technology-based sector of the US economy, especially manufacturing, have begun to form. Unfortunately, budget deficits and the consequent ratio of US debt to GDP are much higher today than in the 1960s, providing substantial barriers to needed adaptive efficiency.

The other major barrier to the needed policy response is the almost total focus on 'macrostabilization' (monetary and fiscal) policies. While these policy mechanisms work reasonably well in normal economic downturns, more serious declines that are the manifestation of underlying structural problems will not be adequately mitigated by them. In such cases, macroeconomic stimulus efforts generate at best weak multiplier effects. The globalization of markets further reduces the fiscal multiplier traditionally expected from short-term stimulus. The result is that the economy does not attain self-sustaining growth. Debates over amounts and types of government spending become increasingly bitter, as political factions argue over how to divide up a stagnant economic pie.

Self-sustaining growth can only result from investment in productivity-enhancing assets based on regular advances in technology. However, even the largest R&D-intensive companies will not have the total complement of internal research and production assets to realize the full potential benefits of investment in new technology platforms. Further, new technology platforms are typically developed years in advance of initial commercialization. Thus, the higher discount rates now applied by companies to R&D investments are leading to declining investment in the radically new technologies that will drive the industries of the future. These higher discount rates are the result of the combined increases in technical and market risk resulting from compressed global technology life cycles.

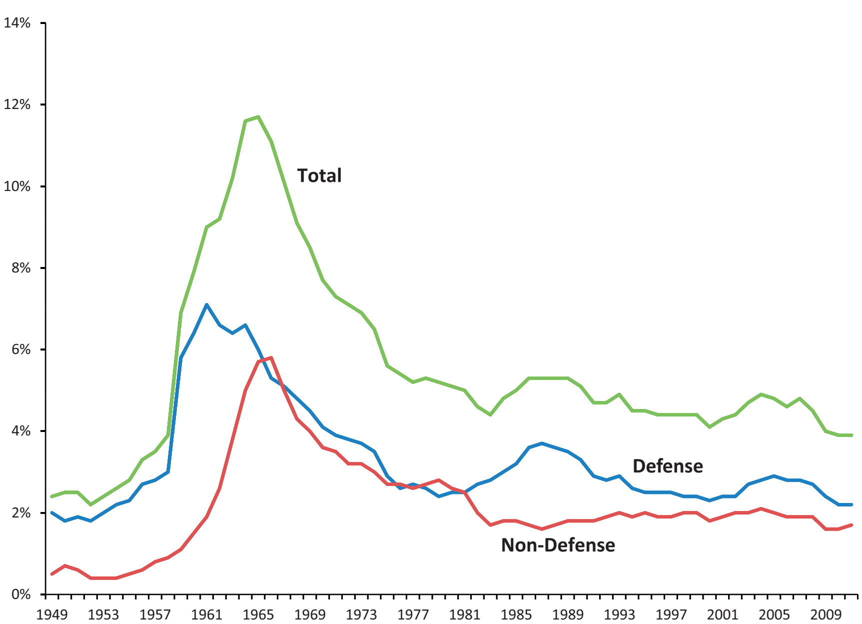

Figure 8. Federal R&D as percentage of total outlays, 1949–2009.
Source: OMB Historical Table 9.7.

The overall policy response is to create a national innovation system that will be characterized by first, increased joint industry–government strategic planning for the technology-platform and infratechnology elements of emerging technologies; second, a more elaborate and better defined set of public and private research roles through application of the technology-element growth model; and third, movement toward a holistic innovation system, which supports the complete technology life cycle; i.e., the STID phases of modern technology-based economic growth.

In the end, only two generic growth policy options are available: first, accept lower wages and prices to expand global market shares, which will also lower the standard of living; or, second, grow faster by investing in the set of productivity-enhancing assets identified in this paper, which will raise the standard of living.

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Notes

1. Atkinson and Audretsch (2008) provide an excellent comparative assessment of the alternative dominant major economic growth policy philosophies in terms of their respective approaches to achieving allocative and productive efficiency. In addition, they describe a third growth philosophy, innovation economics, which adds adaptive efficiency as a third policy target. Audretsch and Link (2012) elaborate on the weaknesses of neoclassical economic growth theory and add an assessment of Schumpeter's innovation theory.
2. A NBER study found that the average productivity advantage of the USA over OECD countries as a group accounted for three-quarters of the per capita income difference (McGuckin and van Ark 2002).
3. While three-quarters of US industries contributed to the acceleration in economic growth in the late 1990s, the four IT-producing industries were responsible for a quarter of that acceleration while only accounting for 3% of the GDP (Jorgenson 2005).
4. For example, Paul Krugman in several editorials in the *New York Times* stated that:

   > . . . all the facts suggest that high unemployment in America is the result of inadequate demand . . . structural unemployment is a fake problem, which mainly serves as an excuse for not pursuing real problems . . . (26 September 2010)
   >
   > . . . talking about competitiveness as a goal is fundamentally misleading. (23 January 2011)
   >
   > Many pundits assert that the U.S. economy has big structural problems that will prevent any quick recovery. All the evidence, however, points to a simple lack of demand, which could and should be cured very quickly through a combination of fiscal and monetary stimulus. (2 May 2012)

   See also Krugman (2009).

   In an interview with the *Washington Post*'s Ezra Klein ('More from one of Obama's Keynesian all-stars', 31 July 2011), Lawrence Summers (former Director of the National Economic Council) challenged the view that:

   > . . . macroeconomics was about reducing the variability of output over time, not raising its average level.

   He also argued that:

   > Keynes focused on raising the average level of output through time by raising demand.

   He further stated that the current economic problem:

   > . . . is about demand, not some kind of structural factor in which there are mismatches between the kinds of workers available and the kind employers are seeking.

5. A recession trough is determined by the NBER from a set of economic indicators (employment, real sales etc.).
6. With respect to economic growth policy, value added is the bottom-line metric. In economic accounting terms, it is largely the sum of payments to labor (wages and salaries) and payments to owners of capital (profits).
7. Work stoppages of more than 1,000 workers averaged approximately 300 per year for the first three decades after World War II. After 1980, however, the rate declined precipitously to an annual average of 16 since 2002. Source: Bureau of Labor Statistics <http://www.bls.gov/news.release/wkstp.t01.htm> accessed 02 December 2012. The decline in the impact of unions is partly due to the increasing heterogeneity of worker skills, but a major force has been the pressures of globalization.
8. 'People and profitability, a time for change: A 2009 people management practices survey of the manufacturing industry', Deloitte, the Manufacturing Institute, and Oracle.
9. The US primary educational system, kindergarten (K) through 12th grade, has become a general education process, increasingly inadequate for the highly technical jobs in major portions of the manufacturing and service sectors. Other countries such as Germany offer distinctly different career paths that target technical skill categories needed by globally competitive industries. Follow-on education in US two-year community colleges is largely directed at moving students on to 4-year liberal arts colleges. In contrast, the German educational system tracks students to skilled manufacturing jobs through an elaborate educational infrastructure. For example,

the German Fraunhofer Society model includes successful approaches to training and transitioning new skilled workers to small firms. With respect to higher education, NSF data show that the US now accounts for only 4 percent of the world's engineering degrees, while Asia produces over one-half of the world's total (http://www.nsf.gov/statistics/seind12/c0/c0s4.htm).

10. National Tax Foundation 'Putting corporate tax 'loopholes' in perspective'. The report is available from the Foundation at <www.taxfoundation.org/publications/show/26580.html> accessed 02 December 2012.
11. Source: Bureau of Economic Analysis and McKinsey Global Institute. Data compiled by McKinsey (see Manyika et al. (2011)).
12. A few noted economists, such as Douglas North and Paul Romer, have emphasized the critical role of technology in economic growth, but their views have been largely swamped by the dominant neoclassical and Keynesian economic philosophies (Atkinson and Audretsch 2008: 2).
13. R&D intensity is the amount of R&D spending by a firm or industry divided by net sales. For the economy as a whole, it is national R&D spending divided by GDP. R&D intensity indicates the amount of an economy's output of goods and services that are being invested in developing technologies as a means of competing in the future. Larger economies have to spend more on R&D than do smaller economies to maintain an aggregate competitive position in global markets, so it is the ratio of R&D to GDP that should be the policy driver, not the level of R&D spending.
14. The two lower-left un-shaded markers indicate service industries and the industry in the extreme upper right corner, also represented by an un-shaded marker, is software.
15. See Tassey (2007: Chap. 3) for a summary of this literature.
16. This is the case even though one of the R&D-intensive industries, communications equipment, experienced a sharp drop in real output during these time periods due to significant movement to offshore affiliates.
17. A sea-change index is defined by the Industrial Research Institute as the difference between the number of companies indicating a planned increase of more than 2.5% (allowance for inflation) in a particular category of R&D in the forthcoming year and the number of companies indicating a planned decrease in spending in that year.
18. For example, an examination of DARPA's research project portfolio shows a number of targeted technologies that clearly have commercial and hence economic growth potential beyond defense applications, but other projects are just as clearly limited in potential for yielding economies of scope; i.e. market applications beyond defense. This is not a criticism of DARPA. It selects and manages a portfolio of technologies optimized for national security objectives, as it should. However, its portfolio is therefore not optimized for economic growth, so relying largely on its substantial budget is no longer adequate as a national strategy for developing new technology platforms that maximize subsequent rates of innovation and global market penetration. Agencies such as DoE/ARPA-E) support research on new technology platforms, but their budgets are smaller and their research portfolios have similar issues to a degree. As a result, the current government-wide portfolio exhibits overlap in some technology elements and gaps in others.
19. NSF classifies R&D by three phases: basic, applied, and development. The proof-of-concept technology research discussed here is only the first part of applied research.
20. Gary Anderson, internal NIST memo using industry-performed R&D data from NSF (*Science & Engineering Indicators 2012*, Table 4–15: Sources of funds for domestic R&D performed by the company, by industry and company size: 2008) and industry value-added data from the Bureau of Economic Analysis (BEA). BEA value added by industry tables <http://www.bea.gov/iTable/iTable.cfm?ReqID = 5& step = 1> accessed 02 December 2012.
21. Geographic concentration of specific industries ('industry hubs') is also on the rise. These hubs are not complete innovation clusters and therefore are formed largely through private-sector initiative with local government support. See, for example, Emily Maltby, 'Where the action is', *The Wall Street Journal*, 23 August 2011.
22. Industry has complained about the difficulties in negotiating balanced intellectual property arrangements with universities. This problem is evidenced by a 24% decline of industry funding of university research over the past decade. For some insights into university–industry relationships within clusters, see Kenney et al. (2009).
23. Each tier (industry) in a high-tech supply chain has its own synergies, especially between R&D and production. As Dow Chemical's CEO Andrew Liveris put it:

    > ...when you build overseas your R&D will follow. (interview on CNBC, 27 July 2011)

    And, once an R&D capability is established in a country, its economy is set up to compete as an innovator in the next technology life cycle.
24. A decade ago, Nokia was the dominant supplier of cell phones. However, whereas the company once excelled by combining diversified offerings of handsets with efficient manufacturing and strong customer relationship management, all of its success was within one technology life cycle—the standard cell phone. The

company failed, as many do, to plan for and thereby make the transition to the next major technology, the smart phone. The strategic failure resulted from the fact that not just basic design and manufacturing were important for this cycle transition. Operating and other software, for example, are now critical attributes. Research In Motion, Apple, Microsoft, Samsung (and Google with respect to operating systems) have passed them by. Nokia's supply chain (hardware and software components) has crumbled, making recovery even more difficult. Lagging too far behind the evolutionary trend of multiple technology life cycles can present insurmountable obstacles. Nokia eventually reached such a state and had to partner with Microsoft in an attempt to catch up. For the many reasons stated in this paper, the company's strategic error tends to appear across entire industries, leading to substantial loss of domestic value added.

25. The S-shaped performance–price curve is a useful way of characterizing patterns of technology evolution over a life cycle and the consequent policy implications (Tassey 2007, 2010, 2013).
26. One need only examine the organization of large corporate R&D organizational structures to see that this is the case. Central corporate research labs draw upon basic science created in universities to prove new concepts (generic technologies). The resulting technology platforms are then provided to the applied R&D organizations in the company's line-of-business units to develop proprietary market applications (innovations). These research processes are enabled by a variety of infratechnologies, many of which are promulgated as industry standards.
27. The semiconductor industry has approximately 1600 standards without which that industry could not function. Many of these standards embody a measurement infratechnology. A 2007 NIST study estimated that this industry spent US$12 billion on measurement infratechnologies in the period 1996–2006, which generated gross benefits of US$52 billion (in 2006 dollars) <http://www.nist.gov/director/prog-ofc/report07-2.pdf> accessed 02 December 2012.
28. 'The path ahead for the U.S.–China economic relationship', a speech by Treasury Secretary Timothy Geithner to the John Hopkins School of Advanced International Studies, Baltimore, MD on 12 January 2011, detailing the agenda for a forthcoming visit by China's President Hu Jintao.
29. See *A Strategy for American Innovation: Securing Our Economic Growth and Prosperity,* an update to the administration's innovation report from September 2009 <www.whitehouse.gov/innovation> accessed 02 December 2012.
30. Chairman Ben S. Bernanke, 'Promoting research and development: The government's role,' speech at the Conference on New Building Blocks for Jobs and Economic Growth, Washington, DC, 16 May 2011.
31. See 'China mulls $1.5 trillion boost for strategic industries' <http://www.reuters.com/article/2010/12/03/us-china-economy-investment-idUSTRE6B16U920101203> accessed 02 December 2012.
32. Presentation by Robert-Jan Smits entitled 'Prospects and challenges for the European Innovation Union', 18 February 2011. <http://blogs.science.gc.ca/think-pensez-canada/2011/02/18/mobilizing-resources-for-research-and-innovation-the-eu-model/?lang=en> accessed 02 December 2012.
33. This may be too low as a long-term strategy, but given the fact that the EU's current R&D intensity (2%) is even lower than that of the USA (2.8%), it is probably a reasonable intermediate goal.
34. See Tassey (2007: Chap. 3). A partial annotated bibliography of studies of the economic impacts of technology is available <http://www.nist.gov/director/planning/upload/economic_impacts_of_technology.pdf> accessed 02 December 2012.
35. 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 20th 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 19th century (Lucas 2009).

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