

# The Future of National Manufacturing Policy

For several decades, those deciding on U.S. economic growth policy have struggled over the issue of the correct growth strategy. A critical dimension of this debate has been the role the government should play in achieving desired growth rates. Nowhere has this struggle been more pronounced than in the debate over rationales for government support of the domestic manufacturing sector. Philosophies vary from a broadly activist government role to complete *laissez faire*.

The optimal government role depends completely on the underlying economics. In this regard, leading economies have succeeded over time by investing in a set of assets and learning how to manage those assets effectively. The first industrial revolution (1750 to 1850) began as a rudimentary factory system in which small businesses used emerging crude machines and locally available supplies of power to manufacture a fairly limited range of products. By the second industrial revolution (approximately 1860 to 1910), production technologies based on numerous scientific developments had expanded to a wide range of product categories. The critical processing technology characteristics were mass production, interchangeable parts (i.e., standardization), and the assembly line. In the United States, massive investments in new types of infrastructure such as a national transportation network (particularly railroads), electricity, and an expanded and consolidated financial market were critical to the so-called Gilded Age of the late 19<sup>th</sup> century. The driver of advancement in process technology was the growing mechanization, not only of individual industries but also of entire supply chains, which created cheaper ways of making products. The key metric was achieving economies of scale. Machines were designed, plants were organized, and labor skills were specified in order to produce large volumes of undifferentiated products. As Henry Ford famously stated, “Any customer can have a car painted any color that he wants so long as it is black.”

Economic historians will eventually pass judgment on the characteristics of the current drivers of manufacturing: information technology, nanoscience, and systems engineering. Still, regardless of when this information age is determined to

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*Gregory Tasse* is the Director of the Economic Analysis Office at the National Institute of Standards and Technology.

have begun, it is different from the two industrial revolutions. Products will be designed from the atomic level up, enabling both far greater variety and greater quality, and will be manufactured using sustainable methods at lower unit costs.

The opportunities to achieve greatly increased economic welfare through such “mass customization” are huge. Yet, debates rage not only over how to effectively manage and hence maximize benefits from this emerging era of manufacturing, but also over whether an economy need even be directly involved in this sector of economic activity.

### THE POLICY ISSUE

The first industrial revolution required a set of growth policies that provided the necessary categories of infrastructure, given the nature of the important technologies, the needed skills of laborers, and the amounts and types of suitable financing. However, whereas England was the leader in the first industrial revolution, the United States took over that title in the second. Germany was not a player in the first but was a major one in the second. No Asian nations were important in either one. Today’s third revolution has many more candidates for leadership, and it is increasingly likely that no one economy will ever be dominant again.

This fact raises an important question: What are the appropriate economic growth policies for attaining and maintaining a competitive position in global markets? In this regard, two questions are key:

1. What are the roles of manufacturing in this new era?
2. How do the nature of advanced manufacturing technology and the globalization of markets determine the types and extent of supporting infrastructure?

Several things are certain. First, the extent and diversity of global demand and global competition greatly exceed anything previously experienced. As a result, and in spite of the growing complexity of emerging technologies, technology life cycles are actually shrinking. Therefore, every industrialized nation is facing a major test of its economic growth strategy, as was the case at the beginning of both industrial revolutions.

Compounding the political and social trauma that such events cause is the coincident impact of sticking with old out-of-date growth strategies. The result of the latter has been the recent Great Recession and the extremely weak recovery. A 2012 Federal Reserve Board survey shows that the median net worth of American families dropped from \$126,400 in 2007 to \$77,300 in 2010—a decline of 39 percent.<sup>1</sup> The drop in home values is the major factor, but the decline in median real household income is also a contributor. There is no indication of a significant recovery in the foreseeable future. The bottom line is that the U.S. economy has a growth problem, and economic growth is the only way to reduce the national debt and raise real incomes and the standard of living.

## THE INADEQUACY OF STABILIZATION POLICIES

The dominant focus of current economic policies for restoring an acceptable rate of economic growth from the Great Recession is macroeconomic, specifically monetary and fiscal policies. These “stabilization” policy mechanisms are economy-wide in scope and therefore largely neutral with respect to specific sectors, including manufacturing. The underlying assumption is that the structure of the economy is sound; therefore, the policy objective is to redress imbalances that have caused the rate of economic growth to fall below the long-term growth track. In such a situation, conventional monetary and fiscal policies work quite well.

### Monetary Policy

This policy tool is used to address a common situation arising in recessions: credit is both inadequate and too expensive. Lowering interest rates induces consumers to borrow. The Federal Reserve Board traditionally emphasizes lowering short-term rates. Doing so steepens the so-called yield curve: long-term rates become higher relative to short-term rates. As banks basically borrow short and lend long, their average net interest margin increases. This profit incentive results in more loans being made to businesses and individuals.

However, in this last recession, the extremely high level of household debt inhibited consumer borrowing. Furthermore, banks initially had weak balance sheets because of their many nonperforming loans. The result was virtually no response to the Fed’s rate reductions. So, the Fed went to Plan B: it infused huge amounts of liquidity into the financial system by first buying mortgage-backed securities (QE1) and then treasury bonds (QE2). The main objective was to lower long-term interest rates and thereby stimulate the housing market.

Note that this strategy was based on the conventional wisdom that reviving the housing sector was critical to the economy’s recovery. This traditional view persists, even though a major portion of the excessive household debt is mortgage debt. For decades, government has provided every conceivable incentive to American consumers to overspend on housing and they achieved this.

From an economic growth perspective, the increased spending on housing has redirected household funds away from other categories of investment, including productive assets that are supported through purchases of corporate stocks and bonds, including those of manufacturing companies.<sup>2</sup> The Fed tried to further suppress long-term rates through Operation Twist: it sold short-term treasury securities and purchased long-term ones. One has to wonder if the Fed considered the negative effect on banks’ propensity to lend, given the flattening effect this operation had on the yield curve. Finally, quantitative easing puts funds directly into the hands of bond holders and other conservative investors. Some of these funds find their way into stocks; however, such investors are hardly interested in higher risk, and bypass potentially higher-payoff investments such as advanced manufacturing.

The key point here is that the Fed's efforts have had relatively a weak impact on economic growth. Banks have significantly improved their capitalization levels and therefore are more capable of making loans, and consumers continue to restructure their balance sheets by paying down debt. However, household debt relative to income remains high by historical standards and therefore continues to restrain consumption. This constraint on spending is magnified by the fact that real household income has declined over the past decade.

Moreover, in severe recessions like this last one, the policy response of lowering interest rates to zero (or even negative when adjusted for inflation) creates a liquidity trap. That is, consumers become indifferent between investing and holding cash. If they hold cash, the velocity of money slows down and so does economic activity. Finally, although American businesses on average have maintained healthy balance sheets, the lack of attractive investment opportunities is restraining borrowing.

In general—and most important from the perspective of long-term economic growth policy—to the extent that monetary policy is effective, its impact is to raise nominal GDP. But the standard of living rises only when nominal growth exceeds the rate of inflation; that is, when real GDP is positive. About the only benefit of an increase in nominal GDP (i.e., inflation) is that it becomes easier to pay down the debt.<sup>3</sup>

To achieve the goal of substantial real growth over time, the structure of the economy must be sound. Otherwise, the surge in liquidity simply creates inflation. This is an advantage for highly indebted nations because inflation raises nominal incomes and hence tax revenues, allowing the debt to be paid back more easily. However, this impact of monetary policy does nothing for real growth.

## **Fiscal Policy**

Keynesian economists argue that the core problem in recessions is inadequate demand; therefore, government spending is the key policy response, as its effect is to raise consumption. Even so, the amount of spending by itself is not large enough to start and sustain an economic recovery. Rather, this injection of demand creates a multiplier effect. The industries that benefit from the initial consumption respond by creating additional demand in the industries that supply them with the products and services they need to meet the policy-induced demand. If the multiplier effect is strong enough, the economy can reach so-called escape velocity by achieving a sustainable and acceptable rate of growth. However, the multiplier effect appears to have weakened in recent decades in response to the rising share of imports in domestic consumption. More fundamentally, structural weakness, in the form of inadequate productivity levels, significantly constrains the potential for noninflationary stimulus. But, only sustained non-inflationary growth will allow the budget deficit to be eliminated, as was achieved in the late 1990s through massive investments in productivity-enhancing information technologies.

Unlike monetary policy, fiscal policy has the capacity to reduce structural weaknesses if it is directed toward productivity-enhancing investments, including those that would revitalize the domestic manufacturing sector. Unfortunately, most Keynesian economists focus solely on stimulating aggregate demand, independent of its composition. As I argue in the following sections, failure to adequately invest in productivity-enhancing assets is greatly constraining long-term economic recovery.

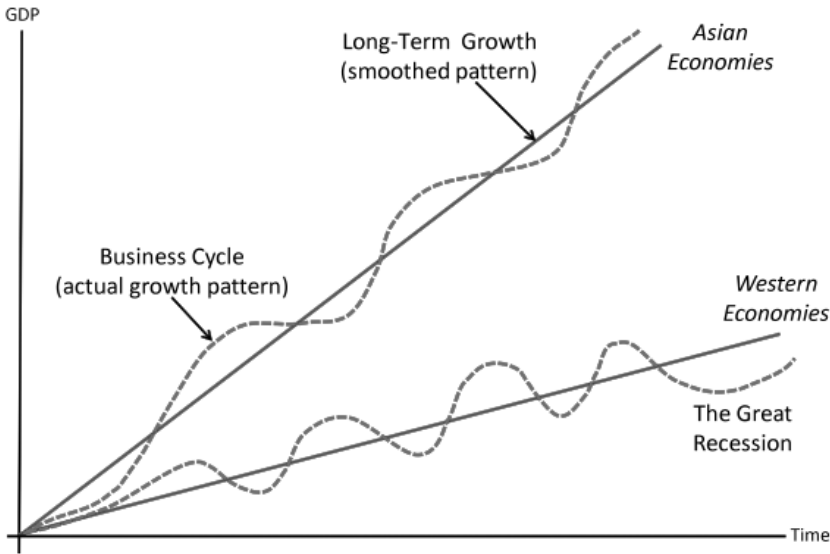
The centerpiece of fiscal stimulation in response to the Great Recession was the American Recovery and Reinvestment Act (ARRA) of 2009, funded at \$787 billion. While ARRA was certainly a major stimulus program, only a modest share of the total funding was directed at investment. Specifically, \$105.3 billion was allocated to traditional economic infrastructure projects (highways, bridges, public transportation, etc.). An additional \$48.7 billion was directed at energy infrastructure and energy efficiency, including a small amount for energy research and manufacturing scale-up. Only \$19.2 billion was allocated to support “scientific research,” including \$5.9 billion to universities. Certainly, ARRA was an aggressive short-term fiscal stimulus strategy. However, the economy’s weak response to this and other fiscal stimuli has led leading economists to call for yet more spending, again without stating any preference for the content of the spending.

Finally, ARRA and other stimulus programs are being financed with deficit spending. To this end, the treasury is currently paying more than \$400 billion per year in interest on debt held by the public. With tight budgets, this is a significant drag on the federal government’s ability to invest in the public economic assets that are required for a competitive economy that seeks to maintain a high standard of living. Furthermore, this interest burden will increase significantly as interest rates rebound from their current historic lows.

In summary, available financial resources must be directed into investments that yield productive assets as the world’s economy is becoming increasingly technology based, accelerating the rates of productivity growth in many countries. The policy message is that only the most efficient existing or newly created economic assets will be viable in the future. To survive, companies, industries, and entire economies will have to become more productive by rapidly assimilating existing technologies and developing new ones.

### **Short-Term versus Long-Term Growth Strategies**

A critical requirement for achieving high rates of economic growth is that very different policy instruments must be used to manage business-cycle fluctuations and the economy’s productive capacity. Fluctuations in economic activity always occur along a long-run growth trajectory, as shown in figure 1. The dashed lines represent these short-run oscillations resulting from business-cycle imbalances. The fluctuations around the trend are managed by controlling a combination of factors: interest rates and the monetary base (monetary policy), and tax rates or government spending (fiscal policy).



**Figure 1.** Long-Term versus Short-Term Growth Trends

The solid straight lines represent different long-term growth trajectories. Their slopes (growth rates) are determined by the relative productivities of unique portfolios of economic assets. Because these assets are accumulated and deployed efficiently only over extended periods of time, well-managed and long-term investment strategies are essential.

A sound economic structure actually leverages the effectiveness of stabilization policies by enabling more efficient investment and productivity responses in recessions and reducing the tendency toward inflation during 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 fluctuations in their business cycles, as exemplified by the top growth trajectory in figure 1. When structural problems are allowed to accumulate and restrain growth rates, debt is frequently used in an attempt to compensate for inadequate growth potential. The destabilizing effect of this approach leads to more pronounced swings in the business cycle. So, in summary, the United States and most European nations are attempting to manage the business cycle within economies with slow growth rates.

#### THE INADEQUACY OF CONVENTIONAL (NEOCLASSICAL) GROWTH POLICIES

If we accept the argument that macroeconomic stabilization policies cannot remediate entrenched structural problems, then we see the need for a more microeconomic-driven growth model. The U.S. manufacturing sector was once considered both a source of economic strength and a symbol of U.S. superiority in the global

economy, but this sector has experienced consecutive annual trade deficits for the past 35 years. At first these deficits were relatively small; some attributed them to the fact that American workers' incomes were much higher than those in the rest of the world, so they could consume more. In other words, trade deficits were rationalized as being a sign of prosperity.

By the mid-1980s, globalization and hence trade were becoming primary growth vehicles for many emerging economies, but also more important for industrialized nations. During this time, however, the U.S. trade balance in manufacturing goods began a trend of pronounced deterioration. Enough people recognized the increasing role of technology in determining relative growth rates across the world's economies so that, in 1988, the U.S. Census Bureau began to calculate a separate trade balance for the subset of products deemed to be technology dependent, which was called advanced technology products (ATP). U.S. leadership in ATP resulted in trade surpluses that lasted until 2002, when even that segment of manufacturing fell into deficit status. The ATP trade deficit has increased each year since then, reaching minus \$99 billion in 2011.

For high-wage economies, automation of existing production processes is the initial response to emerging foreign competition. This has allowed U.S. manufacturing to continue to increase output, even as employment growth stagnated and then began to decline. Meanwhile, the growth of services has led mainstream economists to suggest that manufacturing's shrinking share of GDP, along with its lower labor content, has reduced both its role and its value in the U.S. economy of the future. Following the so-called neoclassical growth theory, traditional economists argue that if all of manufacturing were offshored, it would not be a problem. If relative prices across the world's economies indicate that manufacturing can be done more efficiently elsewhere, then offshoring is the logical and, in fact, the desired consequence.

This view of economic growth and hence the content of economic growth policy completely ignores the integral role that manufacturing plays in the rapidly emerging global technology-based economy. As I detail later, manufacturing is both an essential part of a modern economy's R&D infrastructure and the major source of inputs for rapidly growing high-tech services. Thus, in addition to its contribution to high-paying jobs, manufacturing performs an integral role in leveraging the productivity of other sectors of the economy.

But, even to the extent that it accepts the critical role of manufacturing, neoclassical growth theory does not recognize the fact that modern manufacturing technology is a complex system whose development and utilization is retarded by a number of significant "market failures": multiple areas where the private sector has persistently underinvested.

In the traditional approach to explaining economic growth, buyers and sellers interact in a market. Producers (sellers) react to price changes by reallocating resources. Neoclassical theory asserts that responses to price signals move the market back toward an equilibrium state. But how is the nature and level of this equilibrium determined? This is where the problem arises. While it acknowledges the

existence of and need for traditional economic infrastructure (roads, bridges, etc.), traditional theory assumes that all other relevant economic assets, including technology, are private goods. If this is the case, industry is completely capable of reallocating resources in response to price signals, including making optimal investments in technology.

A second flaw in neoclassical growth theory is the implied assumption that all industries and even entire sectors, such as manufacturing, are independent of each other. This view is compatible with a “black-box” model of technology-based growth in which commercial versions of technologies are plug-and-play entities. That is, each element (a specific technology within a technology system) is functionally independent of other elements. This, in turn, implies that system-level productivity is meaningless or at least is a trivial concept.

In the neoclassical growth model, governments can play a number of “environmental” roles. For example, governments provide a skilled labor force and ensure plentiful and inexpensive capital. To make sure the return on capital is adequate, governments attempt to minimize both taxes and regulation. In such an environment, industry will reallocate resources appropriately and thereby achieve *allocative efficiency*. Because of this simplistic view of technology-based economic growth, traditional growth theory argues that if achieving allocative efficiency includes reallocating assets totally away from manufacturing, so be it.

Equally important, an accepted government role is to ensure adequate competition exists. Sufficient competition is required to ensure *productive efficiency*. This condition ensures that when relative prices change, companies will not only reallocate and/or develop new resources as needed for the product/service mix that defines the new equilibrium growth track, but also that they will produce them at minimum cost. Therefore, adequate competition, combined with the other environmental factors that affect private investment decisions (taxes, regulation, credit availability), results in optimal growth rates. In summary, traditional theory argues that there is no such thing as internal conditions for market failure; this implies, in turn, that government roles lie solely outside the marketplace in the areas identified above, plus funding scientific research at universities.

Keynesian and neoclassical economists still dominate policy advisory positions and therefore block access by decisionmakers to microeconomic growth theories, especially those focused on innovation economics. For example, Christina Romer, former chair of President Obama’s Council of Economic Advisers, criticized her former boss for advocating government policies aimed at improving the competitiveness of U.S. domestic manufacturing.<sup>4</sup> Romer argues that no market failures exist in manufacturing. Therefore, besides ensuring adequate competition, government’s only role is to support basic science and external (to the industry/market) factors, such as education and “infrastructure.” This is the standard neoclassical theory. Ironically, mainstream economists acknowledge the public-good content of traditional infrastructure, but they remain oblivious to the fact that modern high-tech industry functions on a range of technical infrastructures without which it cannot be globally competitive. Romer then endorses the singu-



lar Keynesian diagnosis that the economy faces “a profound shortfall in demand” that is “truly a terrible market failure, and it warrants government intervention.”

Even the widely read and respected *Economist*, in an article on the digitization of manufacturing, argues that “as the revolution rages, governments should stick to the basics: better schools for a skilled workforce, clear rules and a level playing field for enterprises of all kinds. Leave the rest to the revolutionaries.”<sup>5</sup>

The bottom line to the above discussion is that the conservative (neoclassical) approach presumes to simply reduce costs through the adequate availability of capital (and hence lower interest rates), less regulation, and lower taxes. The fundamental problem with this strategy is that at best it promotes more investment in the existing portfolio of products. Neoclassical economics also says that changes in relative prices will efficiently reallocate resources, including investment in new products. But, this principle only works if all products—and their underlying technologies—are purely private goods. In an increasingly technology-based global economy where new technologies are increasingly complex, the private sector is increasingly underinvesting in the public-good elements of these technologies.

Thus, we see the two most important characteristics of neoclassical economics: (1) government intervention of any type that is internal to the dynamics of the private market is viewed as interfering with allocative efficiency, implying that very few market failures exist; (2) the price mechanism maximizes allocative efficiency relative to a given productive efficiency. However, neoclassical economics says little about key questions: How are the choices for allocating resources determined? How is the existing level of productive efficiency achieved? How does it change over time? The dynamics of long-term growth and competitiveness are therefore left to the innovation economists, who provide the elements of what Atkinson and Audretsch call adaptive efficiency, which in turn drives long-term productive efficiency.<sup>6</sup>

## POLICY DELUSIONS

Many analysts have cited the modest gains in production and employment in the postrecession U.S. economy as an indication that a sustainable recovery is emerging. One reason given is some “reshoring” of manufacturing from China and other emerging economies. However, the trumpeting of this trend by economists and business analysts, who attribute it to rising wages in developing economies and the rekindled recognition of the need to be near customers, ignores the fact that productivity is also increasing in these countries. In other words, we are not dealing with perennially low-productivity competitors who compete largely on cost. Over time, the historical process of convergence will continue.<sup>7</sup>

For example, Foxconn, a major Taiwanese supplier of electronic components with major operations in China, began to experience compression in its profit margin in the current decade as Chinese labor costs escalated. But this trend will provide short respite at best for competing industrialized nations, as Foxconn and other Asian companies are responding by automating quickly. In 2011, Foxconn

announced that it planned to use one million robots by 2014, up from about 10,000 robots in 2011 and an expected 300,000 in 2012.

Another delusion is the belief that the competitiveness of the U.S. domestic manufacturing sector can be restored by depreciating our currency. Although the dollar index declined 34 percent in the past decade (2002–2011) against a basket of major currencies, the United States incurred ever larger trade deficits. The fact is that no economy has ever prospered by depreciating its currency. The cost of this strategy is inflation in import prices. Its only legitimate use is to buy time by temporarily increasing domestic value added while the structural problems that caused the long-term trade deficit are removed. Unfortunately, many U.S. competitors around the world are also, to varying degrees, attempting to compete by debasing their own currencies, which is diluting any short-term positive effect this strategy might have had.

Part of the delusion of traditional neoclassical economics stems from its origin in the Industrial Revolution. Not only does this still-dominant growth philosophy oversimplify the nature of technology assets; it also ignores evolving differences in the postcommercialization scale-up process. The Industrial Revolution was built on economies of scale. In neoclassical thinking, this was legitimately a totally private activity. The structure of the production technology was fixed and the labor required to use it was highly homogeneous.<sup>8</sup> Bigger was always better, as economies of scale were significant. And, as long as capital markets were efficient (a requirement of the neoclassical model), industry responded to relative prices by investing in huge plants. In other words, the marketplace achieved allocative efficiency. For this traditional growth model to work, relative prices had to be fairly stable over extended periods of time.

However, in today's emerging highly technology-based global manufacturing economy, companies are better able to change relative prices quickly, due to more rapid and diversified technological change. The pattern of change is no longer just a matter of rapid product development. Process technology is increasingly able to offer on-demand alteration of products' attributes to meet the needs of growing and diversified global markets. In essence, this phenomenon has shifted the basis of competition from economies of scale to economies of scope.

To achieve economies of scope, however, production technologies must use complex, flexible IT-driven systems. Both the hardware and software components of such systems have to be capable of rapid and precise adjustment in response to changing demands from customers. The development of such manufacturing systems requires a wide range of component technologies that collectively are beyond the internal R&D capabilities of single companies, even large ones.

This last point leads to a delicate subject: the future role of the entrepreneur. American culture, perhaps more than that in any other society, has accentuated the role of the individual. This view has been a positive force in U.S. economic growth because it has facilitated creativity and risk-taking. U.S. economic history is filled with stories of product technologies (e.g., the Apple computer) being invented in

garages, which have jump-started new industries and hence delivered considerable economic growth.

Today, however, the complexity of the underlying technologies increasingly prohibits developments in the so-called Pasteur's quadrant of innovation space, where technologies are developed before the underlying science and generic technology platforms are understood.<sup>9</sup> Instead, new manufacturing technology platforms must now be systematically developed through public-private partnerships in order to pool risk and complementary R&D assets from diverse sources. Virtually every industrialized nation on earth is in the process of implementing such partnership infrastructures.

This fundamental shift in the invention stage of technology-based economic growth does not mean that high-tech startups will decline or that venture capital will become increasingly difficult to find. In fact, the complexity of advanced processing technologies offers a broad set of opportunities for small firms at the component level. But both the startups and their sources of financing will have to be more deeply embedded in elaborate innovation infrastructures, such as research consortia or clusters.

#### UPDATING THE NEOCLASSICAL GROWTH MODEL TO SUPPORT AN ADVANCED MANUFACTURING SECTOR

The characterization that I have offered here, of the traditional economic basis for government roles in supporting technology-based economic growth, does not lead to anything approaching the set of policies that U.S. manufacturing will need if it is to be competitive in the future. Specifically, this antiquated view of both industry and government roles in a modern economy leads to the position espoused by traditional economists: that no market failures exist beyond basic science.

I argue that to overcome these fundamental weaknesses of economic thought, the stages of R&D, scale-up, high-volume manufacturing, and market-share growth exhibit significant market failures and therefore require government intervention in various forms. That is, the rationale for updated policies derives from the nature of the processes of developing and using manufacturing technologies.

Furthermore, the argument made by traditional economists and conservative politicians—that proponents of new and expanded government roles in support of advanced manufacturing are asking for special treatment for this sector—misses the point. Any technology-based industry, whether it be manufacturing or services, is dependent on a complex technology platform and a supporting technical infrastructure.<sup>10</sup> The types of market failures are varied,<sup>11</sup> and therefore so are the efficient policy responses.<sup>12</sup>

The overall economic growth policy question is not whether manufacturing is unique, or different from other sectors. Rather, the issue is whether it is a central and essential part of a modern technology-based economy, without which that economy's growth would be significantly restrained. The answer to this question is the essential first step in managing growth policy.

## Why is the policy problem important?

Five economic rationales explain the need for an active government policy to support advanced manufacturing:

1. As an independent economy, the value added produced by the U.S. manufacturing sector would rank 9<sup>th</sup> in the world: it contributes \$1.7 trillion to GDP and employs 11 million workers. Replacing that amount of GDP with jobs that pay the same, or better, in any reasonable period of time is unlikely.

2. Manufacturing contributes to a diversified economic structure, which in a highly competitive global economy is essential to offset increasingly frequent shifts in relative competitiveness and global demand across industries. Traditional economists argue that it would be perfectly acceptable if the U.S. economy became totally service oriented, as if high-tech services are somehow immune from foreign competition; in fact, high-tech service jobs are increasingly “tradeable,” and 30 national economies have policies in place to promote exports of services.<sup>13</sup>

3. Manufacturing accounts for 70 percent of R&D performed by U.S. domestic industry and a 60 percent share of the scientists and engineers employed in U.S. domestic industry. Therefore, the loss of domestic high-tech manufacturing would seriously erode the overall U.S. R&D infrastructure.

4. Fast-growing high-tech service firms are highly dependent on manufacturing companies for technology. Because high-tech services are complex systems, their design and management require close interaction with the suppliers of technology inputs. In other words, domestic supply-chain integration is important.

5. The majority of global trade is in manufactured products, yet the United States has experienced consecutive trade deficits in manufacturing for the last 35 years. Trade deficits are dollar-for-dollar subtractions from GDP, and the increasingly challenged small trade surplus in services does not come close to compensating.

The motivation to revive U.S. manufacturing has largely been centered on the basic fact that this domestic economic sector has lost a huge number of jobs, both to automation and to offshoring. These two factors, however, have very different policy implications. Offshoring is correctly viewed as an issue of competitiveness. Automation, on the other hand, is assumed to be simply an unfortunate price for remaining competitive. Thus, the relentless decline in unit labor costs is grudgingly accepted. In reality, automation is not the detriment to long-term employment it is made out to be. The increased productivity resulting from automation leads to larger market shares and hence larger output that, in turn, requires more workers who are highly paid.<sup>14</sup> Germany, with its decades-long emphasis on manufacturing productivity, gets approximately twice the share of its GDP from this sector as the United States, and it does so with manufacturing labor compensation costs that are approximately 25 percent higher than those in the United States.

In contrast, economic studies have found that technologically stagnant sectors experience slow productivity growth and, therefore, above average increases in

costs and prices. Rising prices increase these sectors' measured share of nominal GDP, thereby lowering national productivity growth.<sup>15</sup>

### **What are the major types of underinvestment?**

As pointed out, modern technologies are highly complex systems; they are definitely not simple additions of the productivity of individual components. In fact, component productivity may not have much meaning outside the manufacturing system.

This situation becomes manifest in five types of market failure:

1. The process of developing and incorporating new technologies in production systems results in leaks of technical knowledge (so-called spillovers).
2. High-tech supply chains experience additional (price) spillovers of technical knowledge as they interact in developing and then selling/purchasing new technologies in highly competitive markets.
3. As firms, especially small ones, focus on specific applications of new technology platforms, they cannot realize economies of scope; that is, they can target only a few of the potential markets. This situation reduces the risk-adjusted expected rate of return associated with early-phase (proof-of-concept) R&D that typically exhibits extensive economies of scope.
4. The long process of developing and then assimilating new technologies into production systems results in estimates of investment returns that are strongly discounted, often yielding an insufficient calculation of net present value/internal rate of return to justify the investment.
5. Compared to other categories of investment, the risk levels are high across the entire R&D cycle.

These causes of underinvestment in advanced manufacturing technologies (i.e., market failures) present significant barriers to the optimal level and composition of investment across technologies, their severity and even their character change over the life cycle of a technology.

### **What are the most efficient policy responses?**

As I argue above, the level of consternation over sluggish growth has been particularly high in the United States because, in the decades following World War II, the United States 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 growth rates. Such policies (various forms of neoclassical and Keynesian economics) rely on stimulating some combination of investment and consumption until the economy attains escape velocity—that is, it reestablishes acceptable and sustainable private-sector rates of economic growth.

As Atkinson and Audretsch discuss in detail,<sup>16</sup> the policy prescription for a technology-based competitive economy is to achieve three types of efficiency:

- In *allocative* efficiency (the focus of the neoclassical growth models)
  - the government promotes saving
  - industry uses savings to invest in capital
  - all investment decisions are responses to price signals

*That is, no market failures exist.*
- *Productive* efficiency focuses on the function of internal market dynamics (perfect competition).

*Again, no market failures exist.*
- In *adaptive* efficiency (based on neo-Schumpeterian growth models)
  - the dynamics of modern technology-based competition require productivity-oriented investment
  - investment over periods of time well beyond the planning horizons of the private sector, is adapted to the phase of the technology life cycle
  - joint public-private behavior can affect the nature and length of life cycles

*That is, multiple market failures do exist.*

It is this last efficiency category—the adaptation to changing global demand for and supply of increasing amounts and types of technology—that distinguishes modern technology-based growth from traditional neoclassical growth models.

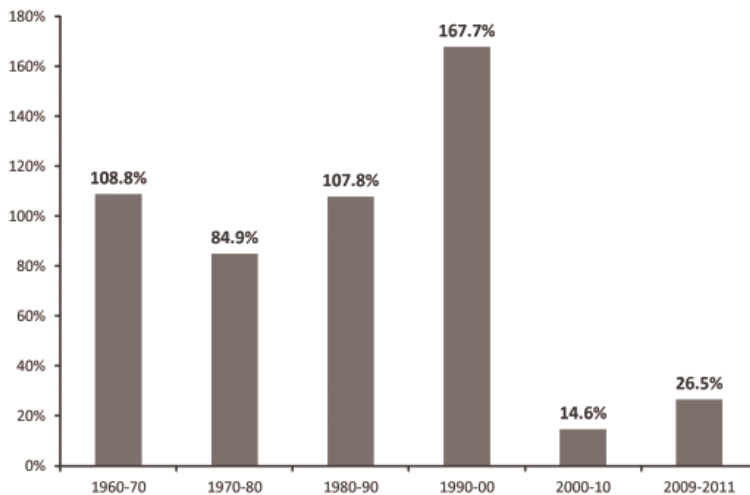
## THE TECHNOLOGY INVESTMENT OPTION

The ultimate objectives of economic growth policy are to create jobs and to increase per capita income. With respect to employment, recent analyses show that with one exception, over rolling 10-year periods, employment and productivity growth have an almost perfect long-term correlation.<sup>17</sup> Moreover, decades of research have demonstrated beyond a doubt that technology drives long-term productivity growth and hence incomes. Data from the Bureau of Labor Statistics 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 percent or more above the overall industry median.<sup>18</sup> 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 multifactor 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. Efficiently achieving these advances depends on investments in multiple drivers besides technology, specifically education, capital formation, and industry infrastructure.

Capital formation is a critical investment category because it is largely through embodiment in capital that technology has its economic impact. However, as figure 2 shows clearly, private-sector investment in hardware and software within the U.S. economy stagnated during the last decade, which does not bode well for future

**Figure 2. Fixed Private Investment in Hardware & Software**  
(growth by decade in 2005 dollars)



**Figure 2.** Fixed Private Investment in Hardware and Software (growth by decade in 2005 dollars)

Source: Data from Bureau of Economic Analysis, NIPA Table 5.3.5 (includes both equipment and software) and Table 5.3.4 (price indexes and fixed private investment). Available at <http://www.bea.gov/iTable/iTable.cfm?ReqID=9&step=1>

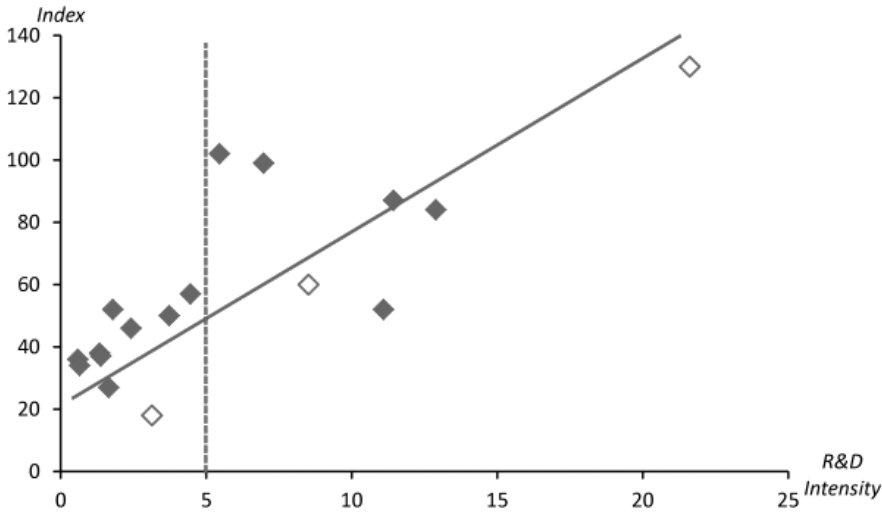
domestic productivity growth. Note that in the last several years investment in hardware and software has shown signs of picking up. This trend has been leveraged by historically low interest rates and record deficit spending by government. As this is an unstable and unsustainable situation, growth policy will have to give much higher priority to this kind of investment.

Clearly, as the driver of long-term growth in the productivity of capital, investment in technology will have to increase as well. 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, a major policy problem is the fact that R&D is not a homogeneous investment, as assumed by neoclassical economic growth models and even by many innovation economists. Therefore, in addition to the amount of R&D, the composition of R&D is a critical strategy metric, as is the efficiency with which each of these variables is managed.

### The Amount of R&D Investment

The amount of spending on R&D has historically been the dominant STID policy metric. However, in spite of a relatively long-term debate over the importance of investment in R&D, the U.S. economy has steadily lost ground with respect to the rest of the world. Specifically, the R&D intensity of the U.S. economy (total R&D



**Figure 3.** Rate of Innovation versus R&D Intensity: Percentage of companies in an industry reporting product/process innovations, 2003-2007

*Note:* Index = sum of percent of companies in an industry reporting product innovations and percent reporting process innovations. *Sources:* Science and Engineering Indicators 2010, Appendix Table 4-14; Mark Boroush, "NSF Releases Statistics on Business Innovation," NSF InfoBrief, October 2010.

spending as a share of GDP) is the same today as it was in the mid-1960s. During that time, an explosion of R&D investment has occurred in the rest of the world. Today, global R&D spending is \$1.4 trillion, most of it in manufacturing. In the last 15 years for which OECD has cross-country data (1995-2009), the United States has increased its R&D intensity by 15.5 percent—one of the lowest among industrialized nations. In contrast, China increased its R&D intensity by 198.3 percent during this same period.

In addition to the pacifist approach of neoclassical economics, another major issue arises here. Although the STID community has argued with increasing force that the United States is underinvesting in innovation and subsequent market development (scale-up), the relatively small size of the “high-tech” portion of the economy (approximately 7 percent of GDP) has left it in a relatively weak position politically with respect to getting the priority status for needed major policy initiatives.

Although intuitively clear, the importance of the amount of investment in R&D can for the first time be demonstrated using product and process innovation data recently compiled by the National Science Foundation for a broad cross-section of industries. Figure 3 compares an index of industry innovation rates with industry R&D intensities for 17 industries. The index was created by adding the number of product and process innovations for each industry in the National Science Foundation database and plotting this index against the R&D intensity for each industry. A positive correlation is clearly evident, underscoring the impor-



tance of R&D intensity as a major policy variable.

The vertical dashed line in figure 3 indicates the minimum ratio of R&D to sales that typically qualifies an industry as R&D intensive. Ten of the 17 industries fall below this minimum.<sup>19</sup> Over time, these industries will become increasingly less competitive and provide fewer jobs and lower rates of pay.

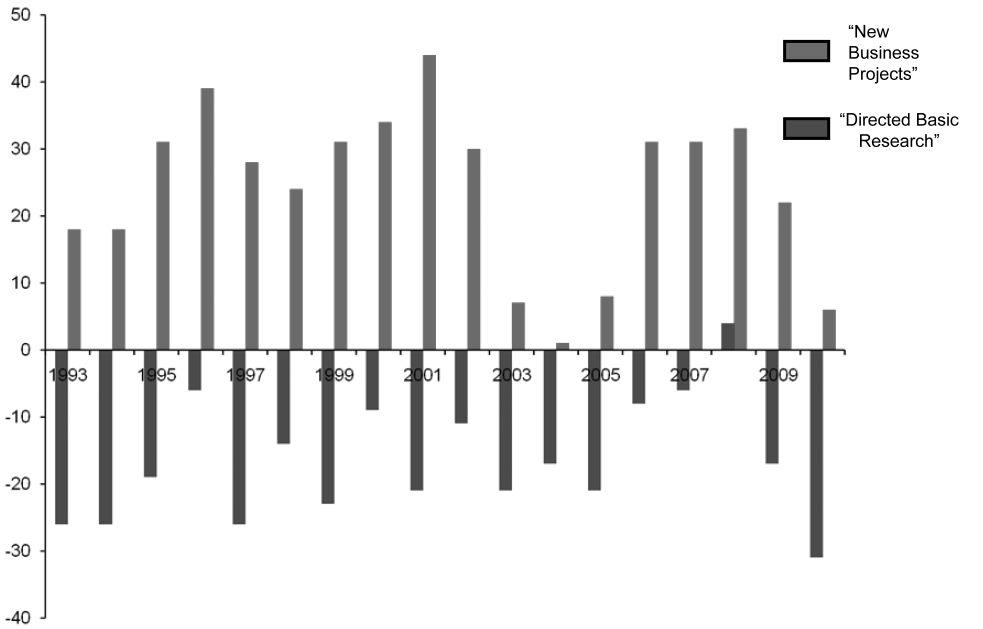
This positive relationship between R&D intensity and innovation is becoming increasingly important. Not only is the \$1.4 trillion spent annually on R&D in the global economy a huge level of investment by itself; it also creates substantial leverage on capital formation for production and subsequent 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.<sup>20</sup> The problem is that the average R&D intensity for all U.S. manufacturing is only 3.7 percent—well below the lower end of what are considered R&D-intensive industries. And, surprisingly, this figure has remained unchanged since the 1980s.

### **The Composition of R&D Investment**

High R&D intensity is no longer a sufficient condition for maintaining a competitive domestic manufacturing sector. An accurate model of technology-based growth recognizes the several phases by which scientific knowledge is turned into successively more applied technical knowledge until the firm reaches the point of commercialization. The earliest phase of technology research seeks to prove the concept of how the technology will eventually provide commercially viable products or processes. This proof-of-concept phase typically occurs a long time before commercialization. Its broad “technology-platform” character provides the potential for multiple market applications; that is, the aggregate potential impact on economic growth is substantial.

However, the private sector has to apply a discount rate to adjust for expected rates of return that will occur only with a considerable time lag and also to adjust for both technical and market risk. As a result, industry significantly underinvests in this earlyphase technology research. Finally, the broad sets of potential 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.<sup>21</sup> For all these reasons, the “valley of death,” as the proof-of-concept phase of R&D is sometimes referred to, is providing an increasing obstacle to the development of new manufacturing technologies.

Figure 4 shows the resulting trend: industry invests less in the radically new technologies with long-term and large economic impact potential that exhibit considerable technical and market risk and capturability problems. Using 19 years of data on annual planned company R&D expenditures from surveys of its members by the Industrial Research Institute (IRI), the bar chart shows trends in two “sea-change” indexes of R&D investment.<sup>22</sup> The light-shaded bars are the annual index numbers for “new business projects”: short-term R&D-aimed market applications



**Figure 4.** The “Valley of Death” is Getting Wider. Trends in short-term versus long-term U.S. industry R&D, 1993-2011.

Source: From the Industrial Research Institute’s annual surveys of member companies’ R&D spending plans for the following year. Most members are in manufacturing; sample size is not constant from year to year.

within current technology life cycles. The dark bars are the annual index numbers for “directed basic research”: 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, U.S. industry has regularly increased its investment in short-term R&D to respond to growing competitive challenges in the global economy, while regularly decreasing its 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. 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 recent modest growth in industry’s R&D intensity topped out in the last decade, as increasing portions of domestic company R&D funding were allocated to other economies. But these and other indicators of technology-based investment are rarely mentioned in the interminable discussions in Western economies of what to do about inadequate rates of economic growth.

In addition to its inadequate size, the federal government’s 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. In the past, many of the technologies resulting from mission-oriented research

have eventually 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 for several decades after World War II, when the U.S. economy dominated the world.

However, the indirect path by which mission-oriented technologies are developed and then later spun off to varying degrees into commercial applications draws out the R&D and hence the technology life cycles. The lengthy indirect process of realizing economies of scope from new technologies is no longer competitive in a world economy that conducts over a trillion dollars of R&D per year and is using increasingly efficient mechanisms to manage this investment; in particular, portfolio management techniques that optimize the new technology platforms for commercial market applications. The severity of the composition problem for the U.S. economy is underscored by the fact that mission R&D spending comprises approximately 90 percent of the total federal R&D budget.

The government has a lower discount rate, the ability to undertake riskier research projects, and the resources to support both a broad portfolio of long-term projects and the interfaces among the results of these projects required for system productivity. Therefore, it must be a major supporter of the elements of complex modern technologies with public-good content. Yet, the government's capacity to contribute in the early part of the R&D cycle to next-generation technologies has steadily declined relative to the size of the economy; its R&D intensity has shrunk from 1.92 percent in 1964 to 0.73 percent in 2008, a decline of 163 percent. It has shrunk even more 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's growth, the decline in industry's own funding of breakthrough research (figure 4) 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 market applications, i.e., innovations). This transition phase (proof-of-concept research) plays a critical economic role. It reduces technical and market risk sufficiently to encourage industry to invest the far larger funds required for applied R&D, and then finally to fund the development phase that creates innovations.<sup>23</sup>

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

## **The Efficiency of R&D Investment**

From a public policy perspective, R&D efficiency is a composite of three factors: (1) the portfolio of technologies pursued relative to the optimum one for maximum economic growth; (2) 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; and (3) 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 R&D infrastructure (research facilities, skills of researchers).

Overall, 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. The cluster model offers an approach to increasing the efficiency of technology-based economic growth strategies through the regional collocation of public and private R&D assets. The collocation 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 the production of new technologies. Moreover, the research consortium element of a cluster facilitates effective management of intellectual property.

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 the management by the entire supply chain of successive technology life cycles through enhanced life-cycle investment coordination, including planning for and public-private cofunding 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 colocated and interacting regularly to cooperate on innovation. However, the "natural agglomeration" of related industries in a supply chain can take a long time to occur. Therefore, a proactive policy approach is required. Unless such synergies are realized through the application of public-private asset growth models, individual domestic companies will find themselves at a disadvantage because they will be competing not only against firms in other countries but also against those countries' governments, which are partnering with their domestic industries.

### **SCALE-UP**

Scale-up is critical to capturing the high value-added potential of new manufacturing technologies. The U.S. economy has a history of being the innovator, only to

lose significant market share as technologies mature. This a critical problem because it is during the middle and later phases of a technology's life cycle that large global markets are created, with the consequent derived demand for large numbers of high-paid workers.

A major barrier is the difficulty that R&D-intensive small and midsize firms experience as they transition from a pure R&D establishment to one with the requisite manufacturing expertise. SMEs provide many innovations and business approaches that contribute to a new technology's market diversity and expansion. This problem of transition is exacerbated by the imperative for advanced manufacturing to provide greater product variety to meet the needs of increasingly diverse customers ("mass customization"), while at the same time maintaining high quality and low unit cost. The complexity and IT-driven nature of the evolving production systems present formidable barriers to scale-up.

As a policy response, a recent report to Congress from the White House recommends greatly increased use of joint industry-government planning, demonstration projects to provide information on the changes in internal company infrastructure needed to assimilate new manufacturing technologies, and shared production facilities that can support SMEs as they acquire advanced production expertise and thereby enable the transition to large-volume but also differentiated, high-quality, and low-cost production.<sup>24</sup>

#### A NEO-SCHUMPETERIAN GROWTH MODEL

In the previous section I described 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 that technology plays in the Schumpeterian tradition. However, the technology-element model also recognizes the complexity of modern technologies and the importance of competitive dynamics in determining comparative advantage among nations.

In this context, firms achieve their competitive positions through the relative efficiency of investment by both government and industry. Unlike in neoclassical economic growth theory, comparative advantage is determined by the efficiency of public-private investment strategies. In fact, the increasingly global scope of private industry's market strategies leaves government as the major differentiator of domestic competitiveness among nations, as it is public investment policies that determine the global flows of R&D and physical capital and the relative efficiencies of industry structures.

However, modern technology-based competition requires two major modifications to Schumpeterian economics. First, the scope of potential market applications of today's technologies is much wider than in the 1930s and 1940s, when Schumpeter wrote his extremely insightful works. As a result, the market structures that develop and commercialize them are more varied. As Audretsch and Link point out,<sup>25</sup> Schumpeter was the first to emphasize the role of the entrepreneur and hence to see 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 capabilities and market strength of large firms, which he argued enabled them to be more efficient and successful innovators.

Today, however, both large and small firms coexist 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 supply chains that deliver new technologies through a pattern of R&D and subsequent innovation that is much more distributed than the industry structure that Schumpeter described.

Second, the complexity of modern technologies requires multiple mechanisms for their development and deployment. As described above, 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 supporting the early phases of R&D where the public-good content is high, to leveraging the transition from the R&D phase to scale-up for commercialization.

In summary, Schumpeter's focus on the role of the large firm is understandable; in fact, it characterized innovation economics fairly accurately until a few decades ago. The current growth model that is 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 associated standards.

As previously discussed, individual companies will at most only invest in portions of the needed "common" infrastructure (also called public-good technologies) for four reasons: (1) the higher time discount rates that industry applies to the needed long-term investment in such breakthrough technology research reduce the future expected value; (2) the complexity of this early phase technology research creates substantial technical risk for any one company; (3) even if innovations are technically successful, the long time to commercialization increases market risk; (4) and the broad scope of potential markets that can be penetrated by commercial applications (innovations) derived from new technology platforms is beyond the strategic scope of virtually all companies, leading to "free rider" (appropriability) problems for any company making the research commitment. The fourth barrier is particularly strong for infratechnologies, as they frequently form the basis for industry standards. Yet, the semiconductor industry, for example, has approximately 1600 standards without which it could not function.

Given the increasing importance and complexity of a modern economy's innovation infrastructure and its pronounced effect on the decisions of global companies about where to invest in both R&D and manufacturing, coupled with its public-good nature, the result is that national governments compete against each other as much as global companies do. This is a sharp departure from the neoclassical growth model and, if the United States does not fully grasp this fact and respond

accordingly, the current weak economic recovery will become a permanent slow-growth track.

Finally, with the world's technology-based economy expanding so rapidly, U.S. dominance of the rate and direction of innovation is rapidly dissipating. Future growth in real income and the standard of living will depend on the degree to which the U.S. economy adapts to the changing competitive imperative, which at the bottom line centers on making major growth sectors, including manufacturing, much more high-tech.

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1. See <http://www.federalreserve.gov/Pubs/Bulletin/2012/PDF/scf12.pdf>.
  2. A good portion of this liquidity found its way into the stock market, raising stock prices. A potential benefit is the creation of a "wealth effect," which can indirectly induce consumption.
  3. This last point explains why the most troubled European economies cannot even buy time to try to fix their underlying structural problems. Since they cannot depreciate their own currencies, they are less able to manage their excessive debt and to increase exports.
  4. Christina Romer, "Do Manufacturers Need Special Treatment," *New York Times*, February 4, 2012.
  5. "Manufacturing: The Third Industrial Revolution," *The Economist*, April 21, 2012.
  6. R. Atkinson and D. Audretsch, *Economic Doctrines and Policy Differences: Has the Washington Policy Debate Been Asking the Wrong Questions?* (Washington, DC: Information Technology and Innovation Foundation, 2008). Available at <http://www.itif.org/files/EconomicDoctrine.pdf>.
  7. Convergence is a cyclical process by which economies catch up with the leaders. In the last four decades of the 20<sup>th</sup> century, convergence accelerated significantly, with several emerging economies doubling their national income in 10 to 20 years, compared with the 30 to 70 years required to do so in the 19<sup>th</sup> century. Robert Lucas, Jr., "Trade and the Diffusion of the Industrial Revolution," *American Economic Journal: Macroeconomics* 1, no. 1 (January 2004): 1-25.
  8. More than any other factor, the homogeneity of labor led to the need for labor unions to counterbalance the ability of management to easily substitute one worker for another.
  9. See Donald Stokes, *Pasteur's Quadrant: Basic Science and Technological Innovation* (Washington, DC: Brookings Institution, 1997); and Gregory Tasse, *The Technology Imperative* (Northampton, MA: Edward Elgar, 2007).
  10. Tasse, *The Technology Imperative*.
  11. Gregory Tasse, "Underinvestment in Public-Good Technologies," in *Essays in Honor of Edwin Mansfield*, eds. F. M. Scherer and A. N. Link, special issue of the *Journal of Technology Transfer* 30 (2005): 89-113.
  12. Gregory Tasse, "Rationales and Mechanisms for Revitalizing U.S. Manufacturing R&D Strategies," *Journal of Technology Transfer* 35 (June 2010): 283-333.
  13. R. Kennedy and A. Sharma, *The Services Shift* (Upper Saddle River, NJ: FT Press, 2009).
  14. William Nordhaus, "The Sources of the Productivity Rebound and the Manufacturing Employment Puzzle," NBER Working Paper 11354. Cambridge, MA: National Bureau of Economic Research, 2005.
  15. William Baumol, "Macroeconomics of Unbalanced Growth: The Anatomy of Urban Crisis," *American Economic Review* 57 (June 1967): 418-420; William Nordhaus, "Baumol's Disease: A Macroeconomic Perspective," NBER Working Paper 12218. Cambridge, MA: National Bureau of Economic Research, 2006. Available at <http://www.nber.org/papers/w12218>.
  16. Atkinson and Audretsch, *Economic Doctrines and Policy Differences*.
  17. J. Manyika, D. Hunt, S. Nyquist, J. Remes, V. Malhotra, L. Mendonca, B. Auguste, and S. Test,

- Growth and Renewal in the United States: Retooling America's Economic Engine*, McKinsey Global Institute, February, 2011. See pp. 5-6 and p. 27.
18. Daniel Hecker, "High-Technology Employment: A NAICS-based Update," *Monthly Labor Review* (July 2005): 57-72.
  19. The three unshaded markers indicate service industries and the industry in the extreme upper right corner is software.
  20. C. Jones and J. Williams, "Measuring the Social Returns to R&D," *Quarterly Journal of Economics* 113 (November 1998): 1119-1135; C. Jones and J. Williams, "Too Much of a Good Thing?: The Economics of Investment in R&D," *Journal of Economic Growth* 5 (March 2000): 65-85.
  21. Tassej, *The Technology Imperative*.
  22. The IRI defines a sea change index as the difference between the number of companies indicating a planned increase of more than 2.5 percent (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.
  23. The National Science Foundation classifies R&D into three phases: basic, applied, and development. The proof-of-concept technology research discussed here is only the first part of applied research.
  24. "A National Strategic Plan for Advanced Manufacturing," report prepared in response to a Congressional directive in the reauthorization of the America Competes Act, February 2012. Available at [http://www.whitehouse.gov/sites/default/files/microsites/ostp/iam\\_advancedmanufacturing\\_strategicplan\\_2012.pdf](http://www.whitehouse.gov/sites/default/files/microsites/ostp/iam_advancedmanufacturing_strategicplan_2012.pdf).
  25. David Audretsch and Albert Link, "Entrepreneurship and Innovation: Public Policy Frameworks," *Journal of Technology Transfer* 37, no. 1 (2012): 1-17.