Journal of Economic Perspectives—Volume 28, Number 1—Winter 2014—Pages 27–48

Competing in Advanced Manufacturing: The Need for Improved Growth Models and Policies[†]

Gregory Tassey

In the last two decades, a growing number of emerging economies first acquired manufacturing technology from external sources and subsequently built a capability to develop it internally, thereby becoming increasingly competitive in technology-based markets. In this process of global economic convergence, Asian economies in particular have combined increasing expertise in manufacturing technology with lower labor and capital costs to "hollow out" formerly US-dominated high-tech supply chains. One result has been a steady deterioration in the US Census Bureau's "advanced technology products" trade balance (see http://www.census.gov/foreign-trade/balance/c0007.html) over the past decade, which turned negative in 2002 and continued to deteriorate to a record deficit of $100 billion in 2011, improving only slightly to a deficit of $91 billion in 2012. The bottom line is that the United States has underinvested for several decades in a set of productivity-enhancing assets necessary for the long-term health of its manufacturing sector.

The first part of this paper provides an overview of the role of advanced manufacturing as a key component of technology-based growth, explains how modern advanced manufacturing differs from traditional manufacturing, and describes the advent of global supply chains. The discussion then turns to the role of research and development in advanced manufacturing, and how it differs from the conventional simplified characterization of such investment as a two-step process in which the government supports basic research and then private firms build on that scientific base with applied research and development to produce "proprietary technologies" that

■ *Gregory Tassey is Research Fellow, Economic Policy Research Center, University of Washington, Seattle, Washington. Previously, he was Senior Economist, National Institute of Standards and Technology, Gaithersburg, Maryland. His email address is gtassey@outlook.com.*

[†] To access the disclosure statements, visit http://dx.doi.org/10.1257/jep.28.1.27

doi=10.1257/jep.28.1.27

lead directly to commercial products. Instead, the process of bringing new advanced manufacturing products to market usually consists of two additional distinct elements. One is "proof-of-concept research" to establish broad "technology platforms" that can then be used as a basis for developing actual products. The second is a technical infrastructure of "infratechnologies" that include the analytical tools and standards needed for measuring and classifying the components of the new technology; metrics and methods for determining the adequacy of the multiple performance attributes of the technology; and the interfaces among hardware and software components that must work together for a complex product to perform as specified.

For modern advanced manufacturing industries of the future, the public good content of these two additional elements implies that the process of "creative destruction" needs to be recast within a public–private investment model. Growing interdependencies exist among small and large firms, entire manufacturing supply chains, and major economic sectors (particularly high-tech services) as well as with an increasingly elaborate supporting set of research, educational, and financial infrastructures. If the public–private dynamics are not properly aligned to encourage proof-of-concept research and needed infratechnologies, then promising advances in basic science can easily fall into a "valley of death" and fail to evolve into modern advanced manufacturing technologies that are ready for the marketplace. Each major technology has a degree of uniqueness that demands government support sufficiently sophisticated to allow efficient adaptation to the needs of its particular industry, whether semiconductors, pharmaceuticals, computers, communications equipment, medical equipment, and some other technology-based industry. The conclusion of the paper explores some implications of this perspective for public policy.

Manufacturing in the Global Economy

The Shifting Role of Manufacturing in Economic Growth

The role of manufacturing in the world's economy is growing and now accounts for approximately 16 percent of global GDP and 14 percent of employment (McKinsey Global Institute 2012). In the US economy, real output in the manufacturing sector was the same in 2011 as in 1999 (Bureau of Labor Statistics n.d.). But within this sector, substantial differential growth rates have appeared among manufacturing industries. Between 2000 and 2009, the five large research and development-intensive manufacturing industries—semiconductors, communications equipment, computers, pharmaceuticals, and medical devices—had an average growth in real output of 27 percent. Meanwhile, the five large traditional industries—chemicals, machinery, electrical equipment, plastics and rubber, and fabricated metals—had an average real output growth of –23 percent (compiled from unpublished Bureau of Labor Statistics 3-digit and 4-digit real output data; see Tassey 2013a, table 1).

For a number of reasons, the advanced manufacturing industries are especially important for a future of good jobs and long-term growth. First, manufacturing provides high-paying jobs whose potential loss should not be taken lightly. In particular, many of these jobs are in research and development. National Science Foundation data show that the manufacturing sector conducts 70 percent of the research and development performed by US industry and accounts for 60 percent of industry's scientists and engineers. Allowing the domestic manufacturing sector to offshore would clearly remove a majority of the private economy's research and development capability. As the global economy spent approximately $1.4 trillion on research and development in 2013—most of it in manufacturing—continued competitiveness will require more and better research and development capabilities in that sector.

Second, on the output side, the manufacturing sector accounts for approximately 50 percent of US exports.

Third, manufacturing also generates considerable demand for support services from other sectors. For example, US-based manufacturing companies stimulate demand for 4.7 million service-sector jobs in areas such as telecom, travel, logistics, banking, and information technology infrastructure (McKinsey Global Institute 2012).

Fourth, analyses by the US Bureau of Labor Statistics show that in all but one of 71 technology-oriented occupations, the median income exceeds the median for all occupations; in 57 of these occupations, the median income is 50 percent or more above the overall industry median (Hecker 2005). Hence, the high-income economy must be the high-tech economy.

The Evolving Nature and Role of Advanced Manufacturing

For most of the post–World War II period, the typical factory consisted of standalone work stations with human-controlled machines—drilling, cutting, milling, stamping. Work passed from one station to the next by actions separated from either the sending or receiving stations. Conditions for success were dominated by the imperative to achieve economies of scale in order to meet demand for large quantities of homogeneous products at low cost.

Emerging advanced manufacturing technology is quite different. A 2011 report by the President's Council of Advisors on Science and Technology (PCAST) defines advanced manufacturing as

> . . . a family of activities that (a) depend on the use and coordination of information, automation, computation, software, sensing, and networking, and/or (b) make use of cutting edge materials and emerging capabilities enabled by the physical and biological sciences, for example nanotechnology, chemistry, and biology. This involves new ways to manufacture existing products, and especially the manufacture of new products emerging from advanced technologies.

The technologically advanced products of modern manufacturing are complex systems. Automobiles used to be largely a modestly complex set of hardware components: engine, drive train, suspension, and the like. Today, the modern automobile contains 17 subsystems for which electronics is a central element. These subsystems are controlled and connected to each other by nearly 100 microprocessors and five miles of wiring (Kurfess 2011).

The production system that manufactures the modern automobile and other complex system technologies is increasingly based on computer-controlled and integrated systems of connected stations, which generate and analyze data on multiple attributes of products at multiple phases of completion, thereby allowing real-time adjustments. Even the transfer of the product between work stations is automated. As the demand for customized or at least semi-customized products continues to grow, manufacturing processes must be increasingly flexible to achieve the economies of *scope* required to serve a set of heterogeneous submarkets. Flexibility while still maintaining high performance and low unit cost can only be achieved through new processing techniques, ubiquitous use of information technology, and a highly skilled labor force. Finally, industry structure will be significantly altered as new production concepts such as 3D printing will enable a range of products to be produced quickly at one installation, thereby ushering in an era of what is coming to be called "manufacturing as a service." So radical are these characteristics of advanced manufacturing and its projected economic impacts that some analysts have labeled this emerging technology as the "fourth industrial revolution."

For this to happen, the above set of manufacturing technologies will have to evolve in terms of both physical characteristics and the complex set of information technology–driven processes that create them. Clearly, part of this paradigm shift is increased automation. Thus, we are witnessing a replay of historical fears of the impacts of automation on employment that have occurred periodically for more than a century (for example, Krugman 2013). However, if automation does not occur, then a domestic manufacturing industry will either move off-shore to low-cost labor economies or, increasingly, to advanced economies that have made the requisite investments in advanced manufacturing technologies. If automation does occur, the labor content per unit of output will decline, but the increased productivity will result in larger global market shares and hence an increased demand for well-paid labor.

One sometimes hears the view that with a combination of automation and outsourcing, advanced economies can become basically service economies, doing cutting-edge scientific and design work together with marketing, distribution, and retail, while the actual manufactured goods are imported from other countries. However, this compartmentalized view of the modern economy is inaccurate. As described in the following section, advanced manufacturing often displays important co-location synergies resulting in benefits to new-product development when manufacturing firms are located close to their research and development efforts and to many of their key suppliers. These synergies arise from the fact that much of the technical knowledge developed in the early phases of the research and development cycle is tacit in nature (as opposed to being codified in, say, patents). As a result, person-to-person interactions are critical to advancing and transferring such knowledge (Goffin and Koners 2011).

In addition, technological complexity demands close interaction between high-tech manufacturing and the service systems (finance, medical, transportation, communication, and so on) that depend on the manufacturing sector's technologies. As a result, many larger R&D-intensive companies with a manufacturing core have substantial (largely business-to-business) service units in an attempt to capture synergies between these two sectors of economic activity. For example, as part of a companywide restructuring in the 1990s, IBM created a strategic focus on software services. In 2012, the company derived 41 percent of its revenues from such services. Similarly, Hewlett-Packard purchased Electronic Data Systems in 1999 as a major strategic step to integrate forward into services, and in 2012 services accounted for 35 percent of revenues. McKinsey Global Institute (2012) estimates that across manufacturing subsectors, service-type activities account for 30 to 55 percent of employment.

Supply Chains for Advanced Manufacturing

Standard microeconomic theory emphasizes decisions of firms and the interaction of firms within the same industry. However, the growing complexity of manufacturing technology has increased the distribution of production and of research and development among a series of related industries. An approach that looks at firms or at industries one-by-one gives insufficient attention to the role and interactions among these industries in a modern technology-based economy.

Co-Location Synergies and the Modern High-Tech Supply Chain

The supply chain is the key unit of analysis for understanding these interdependencies. When domestic consumer-product manufacturers lose market shares, the domestic supplier industries that support them tend to contract as well. As one example, the increasingly sophisticated machine tool industry, which is essential to all discrete parts manufacturing industries, was once a highly competitive US industry. But the US share of global output in machine tools has declined from 20.4 percent in 1980, to 9.8 in 2000, and to 5.3 percent in 2012, according to Gardner Business Media's *The World Machine Tool Output and Consumption Survey*. A major reason is that manufacturing industries using machine tools are increasingly located in other countries, which creates incentives to produce these tools in those economies, near their business customers. China became the largest consumer of machine tools in 2002 and a decade later consumed more than four times as much in machine tools as the US economy. Not coincidentally, China now produces more than five times the US output of machine tools.

The companies at the ends of manufacturing supply chains have been referred to as "original equipment manufacturers," meaning such companies actually produce the product—even if that product is later sold under a different brand name. In most traditional supply chains, the original equipment manufacturer has been the dominant firm in terms of technology development. In the US automobile industry, for example, the "Big Three" of General Motors, Ford, and Chrysler traditionally did most of the research and development for automobiles, and then sent component specifications back up the supply chain for production of these components and even subsystems. However, as the technology content of modern manufactured "systems" (autos, airplanes, personal computers, smartphones, and many other advanced manufacturing products) increased, original equipment manufacturers were forced to outsource increasingly larger percentages of their system technology needs. In effect, research and development migrated backward to earlier tiers (industries) in these supply chains, a phenomenon that has led to greater challenges for managing supply-chain coordination.

A common dynamic is that integrated manufacturers dominate the supply chain for a period of time until the interfaces between components are firmly established and the markets become large. At that point, standardized interfaces and economies of scale allow innovative specialists in individual components to enter the industry. The tier in a supply chain at which this vertical disintegration occurs, known as the "decoupling point" (Christensen, Musso, and Anthony 2004), tends to move backward in the supply chain over time from the final product to subsystems and then to component tiers. As a result, the level and complexity of interactions among these tiers increases over a technology's lifecycle.

By integrating electronics industries, Asian economies have captured co-location synergies and taken over increasingly large shares of the value added in electronics products supply chains. In apparent contrast, many American firms have adopted "design-only" strategies. As one prominent example, Apple does some prototype manufacturing in the United States, but off-shores all component manufacturing and assembly. Samsung, its leading competitor in smartphones, has the advantage of being a co-located vertically integrated electronics company, as evidenced by its ability to turn out new versions of its smartphones at a faster pace than does Apple. Further, the overall quality of its phones has increased rapidly. Although Apple was the innovator in smartphones, Samsung has a 31 percent share of the global market, compared to 13 percent for Apple (AFP 2013).

Still, a superior domestic innovation infrastructure and the difficulties experienced by competing economies in imitating can keep innovative activity within the first-mover economy—at least for a while. An example is semiconductors where manufacturing has moved offshore to a substantial degree, but indicators of inventive activity (as measured by relative patent rates) still show a US-centric pattern, especially for process technologies (Macher, Mowery, and Di Minin 2008). "Fabless" (no manufacturing) semiconductor companies have been successful in the current mature phases of the current CMOS technology lifecycle by adopting highly accurate simulation techniques that drastically reduce the number of expensive and time-consuming iterations of a product's design necessary to enable its manufacture. Off-shore dedicated foundries (the producers), in turn, often do not even operate development-scale fabrication facilities, instead relying on real-time adjustments. Both of these single-phase strategies can work within the middle and later phases of a particular technology's lifecycle. But when a new technology lifecycle begins, both strategies may hit a brick wall. The “fabless” firms will not be able to execute design for new manufacturing requirements without close interaction with manufacturing scale-up activity, and foundries will not be able to adapt to radically new product technologies without close interactions with the ongoing product research and development. Thus, the process of off-shoring the manufacturing component of high-tech supply chains has long-term negative consequences, and especially so, the greater the complexity of the technology and the earlier the technology is in its lifecycle.

A number of Asian economies—particularly China, Taiwan, and Korea—have followed growth strategies that started with a few high-tech industries for which major efforts were made to become competitive. These economies aggressively invested in the five major asset categories characterizing technology-based competition: intellectual capital, physical capital, human capital, industry structure, and technical infrastructure. Such investments have enabled these economies to integrate forward (Korea, Taiwan) or backward (China) from the entry industry (Tassey 2010).

Therefore, global competition is no longer just about the success of individual firms or even individual industries. Instead, it is about achieving and maintaining a competitive position in a global supply chain. The current process of global convergence among the world’s economies is a repeat (although faster version) of a phenomenon that has occurred a number of times over the past several centuries (Lucas 2009). However, there is no intrinsic reason why leading economies have to be caught and passed by determined upstarts—either within or between technology lifecycles. In fact, in the future, no one economy will likely dominate an entire supply chain. Global technology-based competition has simply become too vast. Thus, “second best” strategies will likely be the compromise objective: an economy will attempt to be one of several successful competitors in at least several tiers of a high-tech supply chain.

Supply-Chain Benefits and Costs

The economic rationale for dispersed global supply chains is based on the benefits of decentralized low-cost production and technology specialization. This process is facilitated by ever-improving information and computer technology and the decreasing weight/value ratios of many high-tech products (so that transportation costs are less of a barrier to geographic dispersion). Research and development networks spread risk and combine complementary research assets through a process called “open innovation” (Chesbrough 2004). Such networks, using advanced information and communications technology, have become an integral part of global supply chains and can often function quite well. The underlying premise is that these gains in cost and asset allocation efficiency can overcome language and cultural barriers, currency swings, differences in intellectual property laws, and reduced person-to-person interactions between supplier and customer.

But over longer periods, spreading the supply chain geographically reduces the speed and usefulness of information transfers made possible by co-location, especially during and immediately after transitions to new technologies. In particular, during the early phases of the research and development cycle and again during production scale-up after initial commercialization, new technical knowledge is unsettled, thereby requiring constant adjustment. The tacit nature of such knowledge and the frequent need for its transfer is facilitated by continual person-to-person exchanges.

With this potential tradeoff in mind, advanced manufacturing firms considering outsourcing some key components must weigh short-term production cost reductions for a current technology against the risk of falling behind in the next technology cycle. For example, Boeing's move to a "value-stream" supply chain strategy in which suppliers are located in many different countries created coordination problems that seem to be largely responsible for the two-year delay in flight testing the 787 Dreamliner (Petrick 2009). The geographic dispersion of suppliers and Boeing's consequent difficulties in restructuring its supply chain strategy greatly increased management costs, as well as time delays, and Boeing eventually had to bring some of the subassembly work back in-house (Tang and Zimmerman 2009).

The US printed circuit board industry was once relatively labor-intensive, which led to its off-shoring. Today, its production process is highly automated, with low unit labor content, but the transition to automated production happened in other countries where downstream industries are located. Thus, the majority of the global industry remains in those locations (Asia) near the subsequent tiers in the electronics supply chain—component and final product assembly. According to IPC-Association for Connecting Electronic Industries, the US accounts for less than 5 percent of world production, while Asia's share is 90 percent (IPC 2012).

An example of a current technology lifecycle transition is optoelectronics, which is an increasingly important industry because virtually all of the data moving across the Internet is based on optical systems (photons generated by laser diodes replacing electrons generated by transistors). But the current technology lifecycle is largely exhausted.

Thus, optical circuit technology is beginning to undergo a technology lifecycle transition. The current version of optoelectronics is a discrete technology; that is, each component has its own substrate/chip/package, so that individual components must be physically connected to form a more complex device. However, the emerging new generation of optoelectronics will be an integrated technology; that is, multiple components are simultaneously created on the same substrate, which reduces overall size and improves functionality (faster, smaller, less heat produced). The mature *discrete* technology can be produced more cheaply in Asia. However, if the discrete technology is produced in Asia, then the "installed base" of private economic assets and supporting public infrastructure increase the likelihood that the integrated technology will be established there, too (Fuchs, Field, Roth, and Kirchain 2011). If US firms are to become innovation leaders in the new *monolithic* integrated technology, public and private investment strategies will be needed to accelerate the evolution of and scale-up for initial markets, in spite of the fact that they would be at a cost disadvantage compared to discrete production for a period of time—a common situation when a new potentially superior technology is initially attempting to penetrate a market (Tassey 2013b).

In short, while the potential for short-term gains from globalization of supply chains can be clear-cut for individual companies in the middle and later portions of a technology's lifecycle, the loss of co-location synergies in domestic supply chains and the degradation of the domestic economy's private and public research and production infrastructures make being competitive in the next technology lifecycle more difficult. Repeating this scenario across advanced manufacturing sectors will lower the long-term rate of domestic economic growth.

Metrics of Research and Development Policy: Quantity, Composition, and Efficiency

Researchers would benefit from a better characterization of the research and development process that produce modern industrial technologies. To this end, research and development can be divided into three major dimensions: amount, composition, and efficiency.

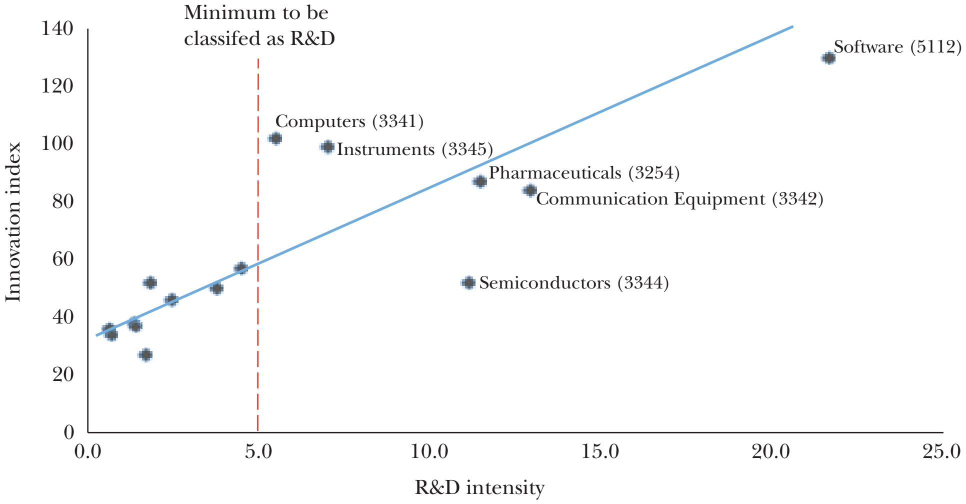
The Quantity of Research and Development Spending

The importance of the quantity of investment in development of new technologies with respect to its impact on innovation can be indicated using data on product and process innovations recently compiled by the National Science Foundation for a broad cross-section of industries. The horizontal axis of Figure 1 shows the research and development intensities for 4-digit NAICS industries or 3-digit NAICS industry groups as measured by the amount of research and development spending by an industry divided by net sales (average for 2003-2007). On the vertical axis, a rough index of industry-level innovation is created by adding the shares of companies reporting product and process innovations for each industry over the period 2006–2008. Product and process innovations are reported separately, so the maximum possible value on the vertical axis would be 200 (percent).

The vertical dashed line in Figure 1 indicates the 5 percent ratio of research and development to sales that has commonly been used (by the OECD, for example) to classify an industry as research and development "intensive." In the figure, 9 of the 14 manufacturing industries fall below this minimum (software is also included because of its ubiquitous use within the manufacturing enterprise, much of it embodied in physical products). For the sector as a whole, NSF data show that US manufacturing's average research and development intensity has increased over a 25-year period from 2.6 percent in the early 1980s to 3.7 percent in 2007. When government funding of US manufacturing company research and development is added, the R&D intensity for 2007 increased modestly to 4.1 percent.

To some extent, any economy will have a mixture of industries that are more-or-less research and development intensive. But the level of research and

Figure 1
Rate of Innovation versus R&D Intensity in US Manufacturing



Sources: Data using data from *Science and Engineering Indicators 2010*, Appendix Table 4-14 for R&D intensity data and Boroush (2010) for innovation data.
Notes: The horizontal axis of Figure 1 shows the research and development intensities for 4-digit NAICS industries or 3-digit NAICS industry groups as measured by the amount of research and development spending by an industry divided by net sales (average for 2003–2007). On the vertical axis, a rough index of industry-level innovation is created by adding the shares (in percent) of companies reporting product and process innovations for each industry over the period 2006–2008. Product and process innovations are reported separately, so the maximum possible value on the vertical axis would be 200 (percent). Note that in each of two pairs of industries (extreme left in plot area), the industry markers overlap.

development should not be taken as an intrinsic limit reflecting innovation potential. After all, technology-based economic growth can include revitalizing existing industries that are currently “low-tech,” requiring a higher research and development intensity.

For the economy as a whole, economists often argue that private firms will underinvest in research and development relative to the social optimum. Indeed, there are six characteristics of research and development that can limit the willingness of advanced manufacturing firms to make appropriate levels and types of investment: 1) high technical and/or market risk with respect to whether the research and development investment will pay off; 2) lead times (investment to commercialization) that are typically longer than for other types of investments; 3) knowledge spillovers of two types: a) the intrinsic nature of knowledge that allows it to “leak” to competitors and b) multiple potential product markets emanating from a technology platform (economies of scope), some of which are beyond the market focus of the investing firm, resulting in a lower expected rate of return; 4) price spillovers in which an innovative firm has insufficient pricing power to capture monopoly rent; 5) information asymmetries between buyers and sellers of technology-based products (buyers cannot verify performance of new products resulting in excess transaction costs and thereby slower market penetration); and, 6) coordination failures between adjacent industries in supply chains that reduce the potential for "open innovation," that is, cooperation in research and development.

Economic studies like Jones and Williams (1998, 2000) have estimated the return on research and development to be four times the return on investment in physical capital, implying that it should increase dramatically. But for modern emerging technologies, the scope of the overall required research on certain key topics is increasingly beyond the research capabilities of even large firms. For decades IBM, like other large research and development-intensive companies, conducted virtually all research within its corporate boundaries. Today, in order to be competitive in the emerging field of nanoelectronics, IBM is a major investor and participant in the Institute for Nanoelectronics Discovery and Exploration located at Albany State University. IBM is partnering with other electronics companies (like Intel, Micron, AMD, Texas Instruments, and Freescale Semiconductor, Inc., as well as with smaller companies who are often suppliers to IBM) and with several universities. The New York State government is a major financial supporter, and the federal government is directly involved in the research (Welser 2008). This investment would be unlikely to happen in anything like the same scope and quantity without this kind of extensive public–private cooperation.

The Composition of Research and Development Spending

US technology policy has traditionally been built on a "black-box" model in which government primarily supports basic science, a consensus public good. In this model, science is then turned into innovations through a private investment sequence based on the view that "technology" is a pure private good. However, corporate organization and investment behavior clearly show that technology investment is not homogenous and that technologies are not black boxes. Rather, the transition from basic science to commercial product includes three major elements: technology platforms, infratechnologies, and proprietary technologies. The two additional elements, technology platforms and infratechnologies, exhibit degrees of public good content.

Once a science base is in place, "proof-of-concept" technology research (as the management literature calls it) typically occurs long before commercialization. The result of such research is the creation of a broad technology-platform, whose existence both confirms the potential for multiple market applications and provides a set of technical conceptualizations that drive applied research and development. One of the best-known examples of proof-of-concept research is Bell Labs' demonstration of the technical concept that semiconductor materials can be organized to perform the functions of an electronic switch or amplifier. The existence of broad economies of scope in proof-of-concept research, together with the high degree of technical and market uncertainty, means that individual firms would be unlikely to capture many of the potential markets from doing this type of research.

To illustrate the problem, the proof-of-concept phase of research and development in the pharmaceutical industry would involve a full conceptual model of the proposed new drug mechanism: specific biological targets, bioavailability, toxicity, and the like. For several decades, the National Institutes of Health spent billions of dollars on life-science research and then waited for private venture capital to fund the development of new proprietary biopharmaceuticals. However, private risk capital does not like to invest in proof-of-concept research—due to the long time to market and the remaining high technical and market risk. So biopharmaceutical firms have attempted to develop new drugs directly from the underlying science, basically by using clinical trials (specifically, Phase II trials) to prove the new drug concept. This approach largely skips a true proof-of-concept phase, because a drug candidate needs to be formulated before a clinical trial, whose purpose therefore is to initially test a specific application of a presumed technology platform. If the technology platform (concept) is not fully developed, application efforts are more likely to be unsuccessful. In fact, Gallaher, Petrusa, O'Conner, and Houghton (2007a) show that Phase II trials have exhibited low probabilities of success for drug candidates advancing through additional clinical testing to approval by the Food and Drug Administration.

Infratechnologies are a diverse set of technical tools that are necessary to conduct all phases of research and development, to control production processes, and to execute marketplace transactions for complex technology-based goods. They include research tools like measurement and test methods, scientific and engineering data, quality control techniques, and the functional as well as physical basis for the interfaces between components of modern technology systems. These tools are called "infratechnologies" because they provide a complex but essential technical infrastructure, which is as critical to achieving adequate private investment for the modern technology-based economy as traditional economic infrastructure was for the Industrial Revolution.

Infratechnologies are often embodied in the standards that are ubiquitous in high-tech industries. The semiconductor industry has over 1,000 standards without which that industry could not function. Gallaher et al. (2007b) estimated that this industry spent $12 billion on measurement infratechnologies in the period 1996–2006, which generated gross benefits of $52 billion in 2006 dollars. Without the availability of this technical infrastructure (most of which is codified as industry standards), costs would be higher not just at the research and development stage, but also during production and even marketing.

In summary, proof-of-concept research, infratechnologies and applied research and development exhibit different degrees of public good content and hence distinctly different investment incentives. Each of these technology elements therefore requires a unique set of policy responses. Basic science is close to a pure public good, which is why it makes sense that the lion's share of basic research is funded by government. Proof-of-concept (technology-platform) research and infratechnology research combine public and private good aspects and are typically co-funded by industry and government; so there is an overall rationale for the evolving partnership mechanisms increasingly observed in the global manufacturing economy. The third element, proprietary technology, is closest to a pure private good, but even in this case, relatively high risk leads to underinvestment, which explains the existence of a "research and experimentation" tax credit.

Clearly, an updated knowledge production function is needed that can better address the major technology elements and their interactions among each other and with the supporting technical infrastructure. In Tassey (2007, 2010), I offer a disaggregated three-element technology production function—showing how the science base is drawn upon to create technology platforms supported by infratechnologies, which then combine to enable the "proprietary technologies."

The Efficiency of Research and Development Spending

The efficiency of research and development policy refers to the organization of research efforts relative to the structure that optimizes the return-on-investment. The appropriate organization will consider the portfolio of technologies needed to achieve complete development of system technologies, with due attention paid to the relative amounts of investment required for each component of that system. It will consider especially the distribution of research and development funding by technology element across the phases of the research cycle: basic research, proof-of-concept research, and applied research and development (infratechnologies are developed and used in all phases). It will further optimize the mix of participants (universities, government, and industry), the mechanisms by which public and private actors collaborate (ecosystem attributes), and the roles of research and development infrastructure (like research facilities and skills of researchers).

Indeed, the attributes of research and development efficiency require a complex organizational format, which is rapidly evolving among the world's technology-based economies. The single most important emerging format, the "regional innovation cluster," has become a global phenomenon. This organizational innovation is a more elaborate version of the stand-alone research consortia that began to appear in the 1980s. The best known of these is SEMATECH, which facilitates development of semiconductors and related production equipment technologies. The cluster model increases the efficiency of technology-based economic growth strategies through co-location of public and private research and development assets within a local area or region. Co-location synergies are achieved through use of the research consortium mechanism, a supporting education infrastructure, involvement of multiple industries in the emerging supply chain, and shared scale-up production facilities to accelerate commercialization.

Clusters can also provide concentrated labor pools with the relevant skills, as well as promoting technology diffusion and hence broader commercialization of research results. A fully functioning innovation cluster can enable management by the entire supply chain of successive technology lifecycles. Moreover, the research consortium facilitates effective management and sharing of intellectual property.

"Additive manufacturing"—frequently called 3D printing—is an example of a complex advanced manufacturing technology that can benefit from more efficient research mechanisms, such as the research cluster. Traditional manufacturing techniques take bulk materials and then drill, cut, mill, or stamp—usually wasting considerable material in the process and ending up with a part made from a homogeneous material. In contrast, additive processing techniques build products by sequentially adding layers of different materials in different combinations and configurations. This approach allows much more complex and varied products or components to be produced by a single production unit, dramatically reducing the retooling and assembly steps. As described by Manufacturing.gov (at http://www.manufacturing.gov/nnmi_pilot_institute.html), "key benefits of additive manufacturing are that it enables shorter lead times, mass customization, reduced parts count, more complex shapes, parts on demand, less material waste, and lower life cycle energy use."

Additive processing technologies require sophisticated materials management and assembly techniques, which must be developed by multidisciplinary teams who first must prove the overall technical concept before processing steps can be specified and integrated into a 3D printing device. Such proof-of-concept research and the follow-on applied research and development are measurement intensive and require detailed processing data and computer models. For example, the average thickness of a layer of material deposited by a 3D printer is now less than 100 microns (a micron is one millionth of a meter). Without sophisticated measurement infratechnologies, the required technology platforms and subsequent product innovations would not be realized.

In summary, thinking about research and development as a heterogeneous, multi-asset investment process, rather than as a two-dimensional mixture of basic research and applied research and development, suggests that the overall efficiency of an economy's research and development effort will be based not just on the level of spending, but on the composition of that spending and how that spending is managed.

The Shifting Strategies of Advanced Manufacturing Firms

When the United States was the world's dominant technological power, large US companies could apply lower discount rates to longer-term, higher-risk research and development projects because they faced relatively little competition and therefore longer technology lifecycles. Technological complexity was sufficiently low so that a single large company could have most of the research and development assets required to pursue major breakthroughs. The provision of infratechnologies and associated standards often evolved slowly over a technology's lifecycle due to inadequate research funding and inefficient standard-setting institutions. However, in the face of weak foreign competition, such lags had minimal negative effect.

The absence of significant competition also allowed companies to expect that they would achieve economies of scope over time by capturing multiple markets based on new technology platforms. For example, IBM once produced an array of electronic components for retail markets in addition to its main product focus, computers. Eventually, it became too difficult to compete with Intel and other specialized chip companies, so IBM shifted to a narrower focus on specialized semiconductor components for use in its own devices. It eventually gave up on the PC, which it helped pioneer. Hewlett-Packard was also both a vertically and horizontally integrated company for most of its history, but in the last 20 years it left multiple lines of business, including measurement and testing equipment for which is was a market leader, retaining only computers, storage, and imaging (printers). Even within these categories, HP narrowed its product scope. For example, in 2011, the company withdrew from smartphones and tablet computer markets, while maintaining its personal computer business line.

For decades, manufacturing corporations have developed technological proof-of-concept (technology platforms) in their central corporate research labs. The applied research and development that results in proprietary technologies is then assigned to the research 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 (labs related to the science and technology of measurement) in semiconductor companies.

More recently, high-tech companies have been allocating more of their research and development budgets to short-term applied research and development, aimed at maximizing profits in the middle and later phases of technology lifecycles, at the expense of long-term research aimed at new technologies (according to 20 years of firm survey data from the Industrial Research Institute discussed in Tassey 2013a, figure 5). Thus, their central research laboratories are receiving a declining share of corporate research and development funds, and increasing portions of these laboratories' budgets are allocated to supporting their business units' applied research and development programs or to assessing external sources of new technologies.

It seems likely that this reallocation of investment is also adversely affecting infratechnologies, which are themselves increasingly complex and often derive from a different science base than the industry's core technology. To understand the role of the public–private good nature of infratechnologies, the National Institute of Standards and Technology (n.d) conducted approximately 15 prospective economic studies of the costs of inadequate infratechnologies across a wide range of technologies and industries, using industry survey data. The results indicate significant underinvestment by industry due to the public good characteristics of the infratechnologies. A larger number of retrospective economic impact studies were conducted of specific government infratechnology research programs based on industry survey data. The vast majority of these studies yielded high estimated rates of returns (Link and Scott 2011). In the few studies where the net economic benefits from government infratechnology investments were low, the analysis indicated that the infratechnology research was being conducted to a sufficient extent by industry. Thus, for the most part, the government infratechnology research programs were found to be addressing significant existing market failures.

The systematic underinvestment by industry in these two quasi–public good technology elements implies that the way in which modern industries seek to address proof-of-concept and infratechnology issues is closely bound up with the ways in which government supports that industry. The pharmaceutical industry has basically tried to force its way to innovation through continued application of the black-box model—in which individual companies seek to build directly on basic science results without sufficient support for proof-of-concept or infratechnology research—with limited success. In contrast, the semiconductor industry has embraced research consortia and investment in infratechnologies and standards. Of course, these industries differ in other ways, too, but part of the difference in their ability to innovate in recent decades can be explained by differences in the type of government support.

To address these underinvestment patterns, industrialized nations are moving at various rates toward the technology-element model described above. Location of investment by global high-tech companies is increasingly affected by the relative efficacy of national investments in the public good portions of these elements. With respect to the previous example of additive manufacturing, the Obama administration has established a National Network for Manufacturing Innovation. One of the first implementations is the National Additive Manufacturing Innovation Institute (NAMII) in Youngstown, Ohio. Importantly, this location is in an emerging technology cluster in the Eastern Ohio–Western Pennsylvania area. As one indication of how such institutional strategies can even attract foreign investment, the giant Asian electronics manufacturer, Foxconn, a "notorious low-wage manufacturer of Apple's iPhone" and hence "a poster child of U.S. outsourcing," will invest $30 million in a new robotics plant in Harrisburg, Pennsylvania. Foxconn was attracted by major elements of the cluster: the NAMII and Carnegie Mellon's world class robotics program to which Foxconn has contributed another $10 million (Muro and Andes 2013).

An Updated Growth Model for Advanced Manufacturing

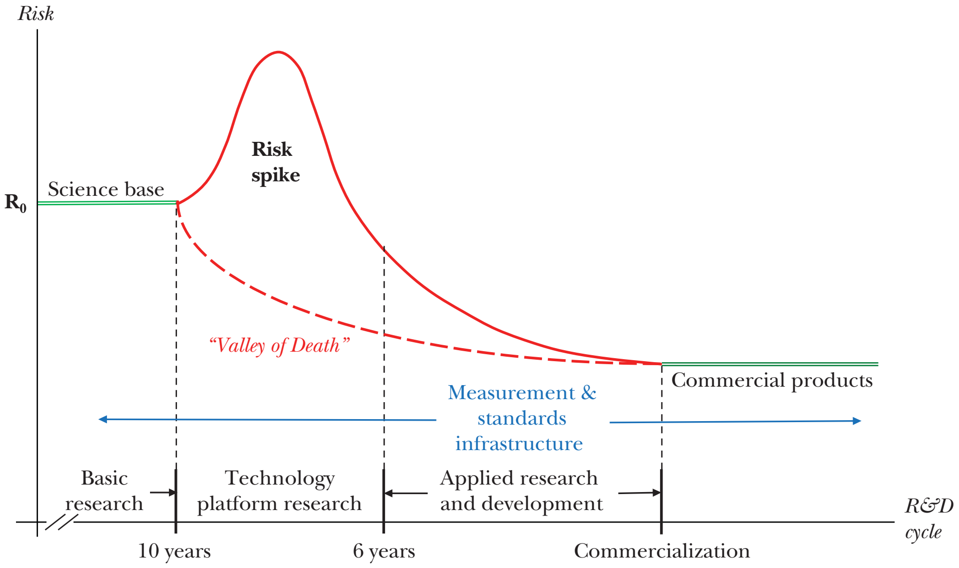
Robert Solow (1956, 1957) characterized the role of technology by using a production function to estimate how much of economic growth could be explained by increases in capital and labor, and then attributing the residual to technology. In these early estimates, the technology residual accounted for about 40 percent of US economic growth. However, both the nature of technology as an economic asset and the investment process by which technical knowledge is created remained to be specified. Moreover, in the traditional economic growth models, technology is a pure private good derived from some exogenous source, which is an implausible assumption for discussions of modern technology policy. Further, the introduction of technology changes the relative productivities of all inputs, as well as the product structure and therefore drives the optimal capital/labor ratio.

This fact alters comparative advantages and creates a second role for technology, that of enabling "adaptive efficiency" as an economy evolves and grows in a global economy (Audretsch and Link 2012). Indeed, the pervasive role of technology has altered the concept of comparative advantage as a superior level of efficiency for one country due to a unique and stable set of endowed assets that create the efficiency advantage. Long ago, a comparative advantage once established could be expected to last for some time. After all, countries' endowments of relatively fixed assets (arable land, mineral deposits, navigable waterways, and climate) remained relatively unchanged and therefore so did relative prices. As manufacturing became a larger share of industrializing economies, the relative efficiencies of deploying capital and labor became more important, hence the focus in Solow's growth model on optimal capital/labor ratios. The optimal capital/labor ratio was determined in part by an underlying set of technologies. However, until the last 50 years, technology changed sufficiently slowly and its sources were frequently considered exogenous so that its role was not explicitly included in growth models. But in the modern economy, the ability of technology to change comparative advantage on a relatively frequent basis makes this input an active part of corporate and national growth strategies, rather than a passive "initial condition."

Three decades after Solow's early work, Romer (1990) introduced an explicit knowledge production function into a general equilibrium growth model. In defining knowledge, Romer distinguished between "rival" and "nonrival" elements of technology. The rival (or excludable) component of technology was embodied in human production capital (and thus part of the tacit component of knowledge referred to earlier). The nonrival component—which in Romer's conceptualization seems to be a disembodied technology element not linked to any specific factor of economic activity—is viewed as partially excludable, and partially not. In microeconomic studies, the production of technical knowledge was mostly characterized as resulting simply from a distribution of past research and development expenditures. Only a very few economists have indicated the possibility of more than a single technology element (Mansfield 1980; Griliches 1986; David and Hall 2000).

Modeling a multi-element technology production function, as described conceptually in the previous section, poses some analytical challenges. It involves specifying multiple categories of technical knowledge, directions of technology element flows and their interaction mechanisms, and degrees of excludability for the different kinds of technology. Within an industry, spillovers occur from one firm to another, among a consortium of firms acting collectively, or to all firms from a source exogenous to the industry (frequently from government or universities). Further, the elements in a technology production function interact with each other. For example, the technology platform drives the productivity of applied research and development. Infratechnologies leverage the productivity of all phases of research and development and also production. For more detail and a formal development of this kind of production function, see Tassey (2005).

Figure 2
Technology Platforms and the Research and Development (R&D) Risk Spike



Source: Tassey (2008).

A critical concept underlying a technology's development and eventual commercialization is a process of risk reduction, as indicated in Figure 2. The horizontal axis is time. The vertical axis represents the level of risk faced by a private-sector technology-based firm considering a course of action that can lead to a commercial product. The traditional view of research and development assumes a smooth pattern starting with a base of scientific knowledge and developing progressively more applied knowledge until a commercial product is produced, which is a pattern of monotonically declining risk indicated by the dashed line.

But when industry begins to consider the possibility of developing commercially viable technologies from an existing science base, it must take into account the significant technical and market risks related to potential commercialization. This significant investment barrier or "risk spike" must be overcome before substantial private investment in applied research and development will be forthcoming. The risk spike is the so-called "valley of death" referred to in innovation policy circles. At this point, the platform technology is immature and the appropriate infratechnologies are ill-developed; thus, initial attempts at innovation solely through company-funded applied research and development frequently fail.

Indeed, on average, the greater the potential of a new technology, the greater the required advance in technology platform development and infratechnologies. That is, the risk spike in Figure 2 will typically be larger for a radically new technology (like one based on a recent major scientific breakthrough) than for investment in less radically new technologies (the next generation of an existing platform technology). Such a risk profile explains why rates of technical progress in the early phases of the research and development cycle targeting radically new technologies can languish for years. However, once the risk spike is overcome, private investment in research and development can flow at sufficient rates to achieve commercialization.

The Policy Imperative

The vast majority of economic debate in recent years has been over ways to overcome the Great Recession and its aftereffects. But policies for business cycle stabilization (monetary and fiscal tools) are far from a holistic long-term growth strategy (Tassey 2013a). In contrast, this paper focuses on structural issues and hence on the strategies that must be resolved for US manufacturing to be globally competitive in the long run. The model of industrial technology development described here implies four important modifications to technology-based economic growth policy.

First, innovation clusters need to be embraced and actively supported. The complexity of modern manufacturing technologies and the shrinking "windows of opportunities" due to intense global competition demand not only more and better-balanced research and development investment, but also more efficient research infrastructures. Specifically, this means geographically concentrating research and development assets from multiple sources and involving several tiers from the emerging high-tech supply chain.

Second, finding ways to reallocate labor as comparative advantage shifts is becoming more important. A few economies, notably Germany, are adept at "reuse of legacy capabilities"; that is, adapting processing and other skills developed for one industry to a newer one (Berger and MIT Industrial Performance Center 2005). This adaptive strategy with respect to labor greatly expands and sustains the acquired expertise in specific processing technologies. The Japanese were also particularly good at "gijutsu yugo" or "technology fusion" during their economy's period of high growth in the 1980s when, for example, they transferred semiconductor processing technology to the new area of optoelectronics (Tassey 1992).

Third, smaller firms are suffering to a greater degree from increasing foreign competition (Petrick 2009). The American Small Manufacturers Coalition (2009) estimates that one-third of small manufacturers (90,000 firms with sales less than $10 million in annual revenue) are not at or near world-class in any element of corporate strategy. For larger firms (more than $100 million in revenue), a smaller share (14 percent) are estimated to be equally deficient. As pointed out by Audretsch and Link (2012), Schumpeterian "creative destruction" initially 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. Schumpeter eventually reversed his view and emphasized the superior capabilities and market strength of large firms, which enabled them to be more efficient and successful innovators. Today both large and small firms coexist in the same technology-intensive supply chain. Each provides complementary assets in the form of components (hardware and software) and their integration to yield the final technology system. In the worldwide emergence of innovation clusters, firms of all sizes agglomerate into integrated supply chains that deliver emerging technologies through a highly distributed pattern of research and development.

Fourth, government policies regarding research and development and innovation will play an important role given the importance of the public–private nexus as advanced manufacturing firms seek to shepherd new technologies through the valley of death to become commercial products. To this end, the current trends are troubling. Federal research and development funding as a percent of GDP was 54 percent lower in 2011 than in 1964, the peak year for this intensity ratio (National Science Foundation n.d.). Moreover, it is not just a matter of the amount a government and the economy as a whole spend on research and development but how it is spent—across industries, over phases of the research and development cycle, among tiers in high-tech supply chains, and through various research infrastructures. The mechanisms for encouraging research and development go beyond direct spending, and also include encouraging various forms of risk-sharing and cooperation not only among competing firms with respect to development of quasi–public-good technology elements, but also between government and industry.

From a broader perspective, the US advanced manufacturing sector faces a potential long-term inadequacy of investments in the five categories of productivity-enhancing assets: 1) technology and intellectual capital; 2) skilled labor; 3) hardware and software; 4) industry structure and behavior (organizational/marketing capital); and 5) technical infrastructure. This inadequacy is not appreciated. Instead, one hears manifestations of an “installed wisdom” effect, which refers to the almost endless stream of rationalizations of how the US economy will continue to be highly competitive without significant change (Atkinson and Ezell 2012, chap. 4, provide an excellent set of examples).

The array of emerging advanced manufacturing platforms will shift leadership positions among the world’s economies. No single economy has yet implemented a complete model for creating and managing a series of domestically focused technology lifecycles. However, some nations like China and Korea in Asia and a number of northern European economies are embracing investments in the required productivity-enhancing assets to a greater degree than others. A few northern European economies have established competitive manufacturing sectors that attain regular trade surpluses, in spite of the fact that average hourly labor compensation costs are much higher than those in the United States (see Bureau of Labor Statistics 2012, http://www.bls.gov/opub/ted/2012/ted_20121221.htm).

Thus, the future of US advanced manufacturing will be determined not only by the efforts of individual companies, although such efforts are of course indispensable, but also by the extent to which the US public–private system for bringing new waves of technology to market is updated and reformed. In the modern global economy, national governments compete against each other as much as do private firms.

■ *The author gratefully acknowledges comments from David Autor, Chang-Tai Hseih, and Timothy Taylor. This paper was reviewed and approved by an internal review board of NIST in February 2013.*

References

AFP. 2013. "Samsung Extends Smartphone Lead over Apple." October 29. http://www.google.com/hostednews/afp/article/ALeqM5ik_noP2mAJhhjanFWYkShVR6qQCQ?docId=c1f3cbed-c8a1-4321-98a2-6782a9141db0.

American Small Manufacturers Coalition. 2009. *Next Generation Manufacturing Study.* (June)

Atkinson, Robert D., and Stephen J. Ezell. 2012. *Innovation Economics: The Race for Global Advantage.* New Haven: Yale University Press.

Audretsch, David B., and Albert N. Link. 2012. "Entrepreneurship and Innovation: Public Policy Frameworks." *Journal of Technology Transfer* 37(1): 1–17.

Berger, Suzanne. 2013. *Making in America.* Cambridge, MA: MIT Press.

Berger, Suzanne, and MIT Industrial Performance Center. 2005. *How We Compete: What Companies around the World Are Doing to Make It in Today's Global Economy.* New York: Currency Doubleday.

Boroush, Mark. 2010. "NSF Releases New Statistics on Business Innovation." *InfoBrief* NSF 11-300, National Science Foundation, Directorate for Social, Behavioral, and Economic Sciences. October.

Bureau of Labor Statistics. 2012. "Manufacturing Compensation Costs in Foreign Countries and in the United States, 2011." December 21. http://www.bls.gov/opub/ted/2012/ted_20121221.htm.

Bureau of Labor Statistics. n.d "Manufacturing Sector and NIPA-level Manufacturing Industries KLEMS Multifactor Productivity Tables by Industry." Available at http://www.bls.gov/mfp/mprdload.htm.

Chesbrough, Henry. 2004. "Managing Open Innovation." *Research-Technology Management* 47(1): 23–6.

Christensen, Clayton M., Christopher S. Musso, and Scott D. Anthony. 2004. "Maximizing the Returns from Research." *Research–Technology Management* 47(4): 12–18.

David, Paul A., and Bronwyn H. Hall. 2000. "Heart of Darkness: Modeling Public-Private Funding Interactions inside the Black Box." NBER Working Paper 7538.

Fuchs, Erica R. H., Frank R. Field, Richard Roth, and Randolf Kirchain. 2011. "Plastic Cars in China? The Significance of Production Location over Markets for Technology Competitiveness in the United States versus the People's Republic of China." *International Journal of Production Economics* 132(1): 79–92.

Gallaher, Michael, Jeffrey Petrusa, Alan O'Conner, and Stephanie Houghton. 2007a. *Economic Assessment of the Technical Infrastructure Needs of the Biopharmaceutical Industry.* Planning Report 07-1, prepared by RTI for National Institute of Standards & Technology Gaithersburg, MD: National Institute of Standards and Technology. http://www.nist.gov/director/planning/upload/report07-1.pdf.

Gallaher, Michael P., Brent R. Rowe, Alex V. Rogozhin, Stephanie A. Houghton, J. Lynn Davis, Michael K. Lamvik, and John S. Geikler. 2007b. *Economic Impact of Measurement in the Semiconductor Industry.* Prepared for RTI International for National Institute of Standards & Technology. Planning Report 07-2. Gaithersburg, MD: National Institute of Standards and Technology. http://www.nist.gov/director/planning/upload/report07-2.pdf.

Goffin, Keith, and Ursala Koners. 2011. "Tacit Knowledge, Lessons Learnt, and New Product Development." *Journal of Product Innovation and Management* 28(2): 300–318.

Griliches, Zvi. 1986. "Productivity, R&D, and Basic Research at the Firm Level in the 1970s." *American Economic Review* 76(1): 141–54.

Hecker, Daniel E. 2005. "High-Technology Employment: A NAICS-based Update." *Monthly Labor Review* 128(7): 57–72.

IPC. 2012. "World PCB Production Report for the Year 2012." (Summary global production share chart in http://www.youtube.com/watch?v=VvB4UJf0nZM).

Jones, Charles I., and John C. Williams. 1998. "Measuring the Social Returns to R&D." *Quarterly Journal of Economics* 113(4): 1119–35.

Jones, Charles I., and John C. Williams. 2000. "Too Much of a Good Thing? The Economics of Investment in R&D." *Journal of Economic Growth* 5(1): 65–85.

Link, Albert N., and John T. Scott. 2011. *The Theory and Practice of Public-Sector R&D Economic Impact Analysis.* Planning Report 11-1. Gaithersburg, MD: National Institute of Standards and Technology. http://www.nist.gov/director/planning/upload/report11-1.pdf.

Krugman, Paul. 2013. "Sympathy for the Luddites." *New York Times,* June 13.

Kurfess, Thomas R. 2011. "The Growing Role of Electronics in Automobiles: A Timeline of Electronics in Cars." June 2. http://www.chicagofed.org/digital_assets/others/events/2011/automotive_outlook_symposium/kurfess_060211.pdf.

Lucas, Robert E. 2009. "Trade and the Diffusion of the Industrial Revolution." *American Economic Journal: Macroeconomics* 1(1): 1–25.

Mansfield, Edwin. 1980. "Basic Research and Productivity Increase in Manufacturing." *American Economic Review* 70(5): 863–73.

National Institute of Standards and Technology. (n.d) NIST Strategic Planning Studies. Available at http://www.nist.gov/director/planning/planning.cfm.

Macher, Jeffrey T., David C. Mowery, and Alberto Di Minin. 2008. "Semiconductors." Chap. 3 in *Innovation in Global Industries*, edited by Jeffrey T. Macher and David C. Mowery. Washington, DC: National Academies Press.

McKinsey Global Institute. 2012. *Manufacturing the Future: The Next Era of Global Growth and Innovation.* http://www.mckinsey.com/insights/manufacturing/the_future_of_manufacturing.

Muro, Mark, and Scott Andes. 2013. "Foxconn Sends a Manufacturing Message with New Pennsylvania Plant." Brookings Institution, November 25, 2013 http://www.brookings.edu/blogs/the-avenue/posts/2013/11/25-foxconn-pennsylvania-muro-andes.

National Science Foundation. n.d. "National Patterns of R&D Resources: 2010–11 Data Update." http://www.nsf.gov/statistics/nsf13318/content.cfm?pub_id=4268&id=2.

Petrick, Irene. 2009. "Supply Chain Globalization: How Surviving SMEs Can Position Themselves for the Future." Chap. 8 in *Manufacturing a Better Future for America*, edited by Richard McCormick. Washington, DC: Alliance for American Manufacturing.

Romer, Paul M. 1990. "Endogenous Technological Change." *Journal of Political Economy* 98 (5, Part 2): S71–S102.

Schumpeter, Joseph A. 1950. *Capitalism, Socialism, and Democracy,* 3rd ed. New York: Harper and Row.

Solow, Robert. 1956. "A Contribution to the Theory of Economic Growth." *Quarterly Journal of Economics* 70(1): 65–94.

Solow, Robert M. 1957. "Technical Change and the Aggregate Production Function." *Review of Economics and Statistics* 39(3): 312–20.

Stokes, Donald E. 1997. *Pasteur's Quadrant: Basic Science and Technological Innovation.* Washington, DC: Brookings Institution Press.

Tang, Christopher S., and Joshua Zimmerman D. 2009. "Managing New Product Development and Supply Chain Risks: The Boeing 787 Case." *Supply Chain Forum* 10(2): 74–86.

Tassey, Gregory. 1992. *Technology Infrastructure and Competitive Position.* Norwell, MA: Kluwer.

Tassey, Gregory. 2005. "The Disaggregated Technology Production Function: A New Model of University and Corporate Research." *Research Policy* 34(3): 287–303.

Tassey, Gregory. 2007. *The Technology Imperative.* Northampton, MA: Edward Elgar.

Tassey, Gregory. 2008. "Modeling and Measuring the Economic Roles of Technology Infrastructure." *Economics of Innovation and New Technology* 17(7–8): 615–29.

Tassey, Gregory. 2010. "Rationales and Mechanisms for Revitalizing US Manufacturing R&D Strategies." *Journal of Technology Transfer* 35(3): 283–333.

Tassey, Gregory. 2013a. "Beyond the Business Cycle: The Need for a Technology-Based Growth Strategy." *Science and Public Policy* 40(3): 293–315.

Tassey, Gregory. 2013b. "Technology Life Cycles." In *The Encyclopedia of Creativity, Invention, Innovation, and Entrepreneurship,* edited by Elias Carayannis and David Campbell. New York, NY: Springer Science + Business Media.

US Census Bureau. n.d. "Trade in Goods with Advance Technology Products." http://www.census.gov/foreign-trade/balance/c0007.html.

Welser, Jeff. 2008. "NIST & SRC Nanoelectronics Research Initiative: Partnership for Innovation." October. http://www.nist.gov/director/vcat/upload/NIST_SRC_NRI.pdf.