



INSTITUTE FOR DEFENSE ANALYSES

Emerging Global Trends in Advanced Manufacturing

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Executive Summary

Introduction

Over the past few decades, manufacturing has evolved from a more labor-intensive set of mechanical processes (traditional manufacturing) to a sophisticated set of information-technology-based processes (advanced manufacturing). Given these changes in advanced manufacturing, the National Intelligence Manager for Science and Technology in the Office of the Director of National Intelligence asked the Institute for Defense Analyses to identify emerging global trends in advanced manufacturing and to propose scenarios for advanced manufacturing 10 and 20 years in the future.

The study team sought to answer the following questions:

- What are *converging trends* in advanced manufacturing across technology areas?
- What are *emerging trends* in advanced manufacturing in specific technology areas?
- What are *enabling factors* that affect success in creating advanced manufacturing products, processes, and enterprises?
- What are *future scenarios* across advanced manufacturing sectors in the technology areas of semiconductors, advanced materials, additive manufacturing, and synthetic biology?

Methodology

The team gathered information through an extensive review of the literature and interviews with almost 90 industry, academic, and government experts recognized as leaders in their fields, known for undertaking transformative research, or with international knowledge and experience.

To illustrate how the landscape of advanced manufacturing might change over the next 20 years, we chose four technology areas for in-depth examination: semiconductors, advanced materials (with a focus on integrated computational materials engineering), additive manufacturing, and biomanufacturing (with a focus on synthetic biology). We selected these areas because they collectively represent broad trends in manufacturing such as mass customization; they can act as platforms upon which other technologies or processes can be built; they are critical to national security; they are influenced by

enabling factors such as intellectual-property rights and protections, regulations, immigration policies, and education quality; and they enjoy a high level of research and development investment in major manufacturing countries.

These four areas have the potential to fundamentally change manufacturing in the next 20 years. Semiconductors and advanced materials are mature technology areas; the last two are emerging technologies, with less certain, but dramatic potential to change future manufacturing.

Converging Trends

The experts we consulted from academia, government, and industry identified five large-scale trends that have been instrumental in the shift from traditional labor-intensive processes to advanced-technology-based processes. They are: (1) the ubiquitous role of information technology, (2) the reliance on modeling and simulation in the manufacturing process, (3) the acceleration of innovation in global supply-chain management, (4) the move toward rapid changeability of manufacturing in response to customer needs and external impediments, and (5) the acceptance and support of sustainable manufacturing. Together, these form an enterprise-level concept of advanced manufacturing where advances in manufacturing occur through tighter integration of R&D and production, mass customization, increased automation, and a focus on the environment without increasing costs or sacrificing performance.

Emerging Trends

Among the mature technology areas, two trends are emerging. First, because semiconductors are the cornerstone of the global information technology economy, multiple areas of research are underway, including the continued linear scaling of silicon-based integrated circuits, increased diversification of materials and approaches to building these circuits, and designing completely novel computing devices. The high risk of these approaches is resulting in many manufacturing supply-chain operations relocating to areas like Southeast Asia, where governments and/or companies are willing to accept such risk, with the consequence that U.S. and other nations' defense and consumer electronic goods may become more susceptible to tampering and counterfeiting.

Second, advanced materials have internal structures with superior properties that facilitate transformative changes in manufactured products. One area with enormous potential for accelerating the insertion of materials into products is integrated computational materials engineering, which uses a systems approach that can reduce costs and schedules and provide technical benefits.

Two trends are also emerging for the less mature technology areas. First, additive manufacturing (which encompasses a variety of techniques for building solid parts by adding materials in layers) has the potential to change how future products are designed, sold, and delivered to customers, making mass customization and easy design changes possible. Two main types of additive manufacturing machines are emerging: consumer-level machines aimed at home use and industrial machines aimed at rapid prototyping and direct production of parts. Second, synthetic biology has the potential to manufacture biological substances from radically engineered biological systems for novel purposes. Synthetic biology, specifically biomanufacturing, could reframe common conceptions of advanced manufacturing.

Enabling Factors

The growth of advanced manufacturing within particular countries depends on factors that a country's government can influence, such as infrastructure quality, labor skills, and a stable business environment, and factors that it cannot, such as trends in private-sector markets. The size of the market and growth potential are the primary reasons why companies choose to locate in a particular country or countries.

Future Scenarios

Our research into advanced manufacturing points to an increasingly automated world that will continue to rely less on labor-intensive mechanical processes and more on sophisticated information-technology-intensive processes. This trend will likely accelerate as advances in manufacturing are implemented.

Over the next 10 years, advanced manufacturing will become increasingly globally linked as automation and digital supply-chain management become the norm across enterprise systems. This trend will be enabled by adaptive sensor networks that allow intelligent feedback to inform rapid analyses and decision-making.

Countries and companies that invest in cyber and related physical infrastructure will be positioned to lead by exploiting the resulting increased flow of information. The underlying expansion in computing and sensing capabilities will, in turn, enhance the importance of semiconductors beyond today's computing and information technology sectors.

Advanced manufacturing processes will likely be more energy and resource efficient in the future, as companies strive to integrate sustainable manufacturing techniques into their business practices to reduce costs, to decrease supply-chain risks, and to enhance product appeal to some customers.

From a technological standpoint, advances in materials and systems design will likely accelerate and transform manufactured products. For example, large global

investments in grapheme and carbon nanotubes for nanoscale applications have the potential to fundamentally change electronics and renewable-energy applications. Further, self-assembly-based fabrication processes and biologically inspired designs will be integrated into the manufacturing process as technologies advance and cost-effective implementations are realized.

Establishing an advanced manufacturing sector will continue to be a priority for many countries, with progress depending importantly on trends in the private sector, such as the size and growth of the market.

In 20 years, many of the early trends and techniques that begin to emerge at 10 years are expected to be more fully adopted, with advanced manufacturing pushed toward new frontiers. Manufacturing innovations will have displaced many of today's traditional manufacturing processes, replacing labor-intensive manufacturing processes with automated processes that rely on sensors, robots, and condition-based systems to reduce the need for human interventions, while providing data and information for process oversight and improvement.

Advanced manufacturing will increasingly rely on new processes that enable flexibility, such as biologically inspired nanoscale-fabrication processes and faster additive manufacturing techniques capable of assembling products by area or by volume rather than by layering materials as is done today.

Over the next 20 years, manufacturers will also increasingly use advanced and custom-designed materials, developed using improved computational methods and accelerated experimental techniques. As computational capabilities increase, materials designs, processing, and product engineering will become more efficient, reducing the time from product concept to production.

In 20 years, synthetic biology could change the manufacturing of biological products. Coupled with advances in genomics, proteomics, systems biology, and genetic engineering, synthetic biology will offer a toolbox of standardized genetic parts that can be used in the design and production of a new system. The catalyst to new products will be increased understanding of cellular functions and disease models.

Summary

This study identified emerging trends in a global economy of advanced manufacturing. Over the next 10 years, advances in manufacturing will likely become increasingly networked. In 20 years, manufacturing is expected to advance to new frontiers, resulting in an increasingly automated and data-intensive manufacturing sector that will likely replace traditional manufacturing as we know it today. An advanced workforce will be needed to develop and maintain these advances in manufacturing.

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1. Introduction

A. Background

The National Intelligence Manager for Science and Technology in the Office of the Director of National Intelligence asked the Institute for Defense Analyses to identify emerging global trends in advanced manufacturing and to propose scenarios for advanced manufacturing 10 and 20 years in the future.

In this report, we use a range of scenarios that take place over 20 years for four technology areas—semiconductors, advanced materials (with a focus on integrated computational materials engineering), additive manufacturing, and biomanufacturing (with a focus on synthetic biology).

The study team found that the United States is strong on most fronts—from investments in manufacturing research and development (R&D) to development of advanced manufacturing products, processes, systems, and enterprises—but because other countries' growth rates exceeds U.S. growth, in 20 to 30 years, the differences will be smaller.

In the United States, almost three-fourths of R&D is in the manufacturing sector, which is one reason many cite the need for a vibrant manufacturing sector (Tassey 2010). The concern is that a reduction in manufacturing would adversely affect the size and efficiency of the U.S. innovation infrastructure, of which advanced manufacturing is a part.

Definition: Gross Domestic Expenditure on Research and Development (GERD)

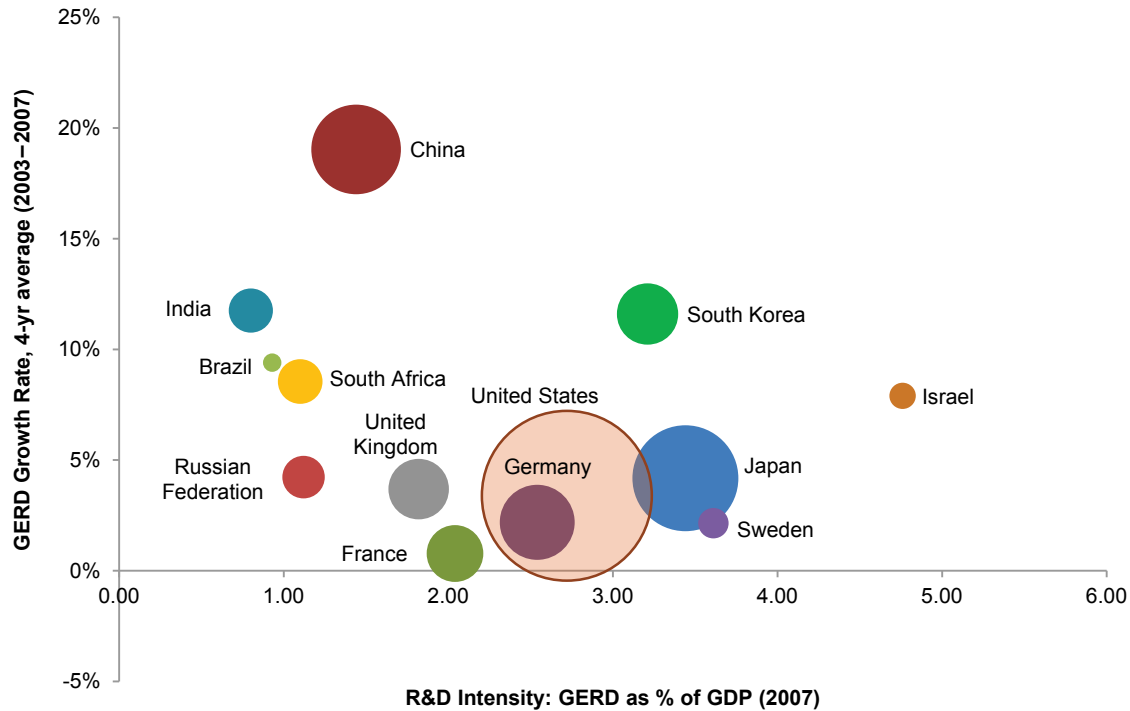
Expenditures for research and development are current and capital expenditures (both public and private) on creative work undertaken systematically to increase knowledge, including knowledge of humanity, culture, and society, and the use of knowledge for new applications. R&D covers basic research, applied research, and experimental development.

Source: United Nations Educational, Scientific, and Cultural Organization (UNESCO) Institute for Statistics.
<http://data.worldbank.org/indicator/GB.XPD.RSDV.GD.ZS>.

R&D spending (referred to as GERD—see sidebar), its growth rate, and its level of intensity (as a percentage of gross domestic product) are indicators of the relative importance a country places on research and development. These measures, individually and combined, show that some countries have higher growth rates and others have higher levels of R&D intensity. Figure 1

plots the level of total R&D spending (the size of the circles), the growth rate (y-axis),

and the intensity (x-axis). The figure indicates that Sweden, Israel, South Korea, and Japan allocate a larger share of their GDP to R&D than the United States allocates; the growth rates for R&D in China, South Korea, and Israel (and other countries) are also higher than in the United States. *The bottom line is that the United States invests the most in R&D (size of the circle), and China has the largest growth rate in R&D (y-axis).* In this report we examine these metrics as predictors of advanced manufacturing strength.



Note: Gross domestic expenditure on research and development (GERD) growth rates by R&D intensity (R&D/GDP) by 2007 R&D purchasing power parity dollars (diameter of circle) (2005 constant dollars).

Figure 1. The United States invests the most in R&D (in absolute dollars), but the growth rate for China is highest.

B. Methods and Study Questions

For this study, we reviewed the literature and interviewed almost 90 industry, academic, and government experts recognized as leaders in their fields, known for undertaking transformative research, or with international knowledge and experience. See Appendix A for a list of the experts we interviewed.

We first defined “advanced manufacturing” (see the next section for details) and conducted a review of global trends based on government investment in manufacturing-related research. We chose four technology areas to examine in depth—semiconductors, advanced materials (with a focus on integrated computational materials engineering),

additive manufacturing, and biomanufacturing (with a focus on synthetic biology). For each technology area, we reviewed investments and policies of selected countries, trends, and barriers to adoption. We selected these areas based on a review of the literature, discussion with experts, and a set of criteria discussed in Chapter 3. We also examined factors that enable advanced manufacturing. Based on these activities, we created future scenarios for advanced manufacturing over 20 years. Our methodology is described in more detail within each chapter.

In our review of the literature and interviews with experts, we sought to answer these questions across the following areas:

- What are *converging trends* in advanced manufacturing?
 - What are common trends that apply across technology areas?
- What are *emerging trends* in advanced manufacturing in specific technology areas?
 - What are broad areas of investment by country or region?
 - What is the current state of two enabling technologies (semiconductors and advanced materials) and two technologies with a less certain but dramatic potential to change manufacturing (additive manufacturing and synthetic biology)?
 - What are global developments in these four technology areas? Are there technology-specific concerns that need to be addressed, from a national security perspective?
 - What advances in science and policies are needed to accelerate changes in these four technology areas to spur changes in advanced manufacturing?
- What are *enabling factors* that affect success in creating advanced manufacturing products, processes, and enterprises?
 - What factors affect where a firm decides to locate?
 - What are the advanced manufacturing investments of other countries of interest?
 - What policies are other countries implementing to ensure that they become preeminent in advanced manufacturing?
- What are *future scenarios* for advanced manufacturing?

C. Defining Advanced Manufacturing

Our definition of advanced manufacturing (see sidebar) is intentionally broad in an attempt to capture all aspects of the topic. *Our definition does not differentiate between traditional and high-technology sectors because new production processes and materials can also transform traditional industries such as the automotive sector.* This definition is based on a synthesis of definitions from peer-reviewed literature and industry press published from 1990 to 2011 (Kotha and Swamidass 2000; Rahman 2008; Sun 2000; Park 2000; Boyer, Ward, and Leong 1996; Noori 1990). See Appendix B for a compilation of definitions from the literature.

Definition: Advanced Manufacturing

Advanced manufacturing improves existing or creates entirely new materials, products, and processes via the use of science, engineering, and information technologies; high-precision tools and methods; a high-performance workforce; and innovative business or organizational models.

Typical characteristics of advanced manufacturing are illustrated in the following descriptions:

- An advanced manufacturing production system is capable of furnishing a mix of products in small or large volumes, with both the efficiency of mass production and the flexibility of custom manufacturing, to respond rapidly to customer demand and desired quality.
- Advanced manufacturing results from substantive advancements (whether incremental or breakthrough) over the current state of art in the production of materials and products; these advancements include improvements in manufacturing processes and systems, which are often spurred by breakthroughs in basic science and engineering disciplines. These new systems, which are often referred to as “intelligent” or “smart” manufacturing systems, integrate computational predictability and operational efficiency.
- Advanced manufacturing produces goods that minimize use of resources while maintaining or improving cost and performance.

As the framework depicted in Figure 2 illustrates, advanced manufacturing involves one or more of the following elements:

- *Advanced products*—Advanced products refer to technologically complex products, new materials, products with highly sophisticated designs, and other innovative products (Zhou et al. 2009; Rahman 2008).
- *Advanced processes and technologies*—Advanced manufacturing may incorporate a new way of accomplishing the “how to” of production, where the focus is creating advanced processes and technologies.

Smart manufacturing and enterprise concepts—In recent years, manufacturing has been conceptualized as a system that goes beyond the factory floor, and paradigms of “manufacturing as an ecosystem” have emerged. The term “smart” encompasses enterprises that create and use data and information throughout the product life cycle with the goal of creating flexible manufacturing processes that respond rapidly to changes in demand at low cost to the firm without damage to

the environment. The concept necessitates a life-cycle view, where products are designed for efficient production and recyclability.

- *Advances in science and technology and the convergence of these technologies are a critical building block of advanced manufacturing.* The framework therefore highlights the role of breakthroughs in physics, chemistry, materials science, and biology, as well as the convergence of these disciplines, as the drivers for advanced manufacturing. Advances in computational modeling and prediction, in conjunction with exponential increases in computation power, also aid this effort. However, we do not assume that advances in manufacturing are solely driven by breakthroughs. *Because substantive, incremental advances can lead to as much innovation in manufacturing as breakthrough advances, breakthrough innovation is not a prerequisite for change that improves the society and economy* (Breznitz and Murphee 2011).

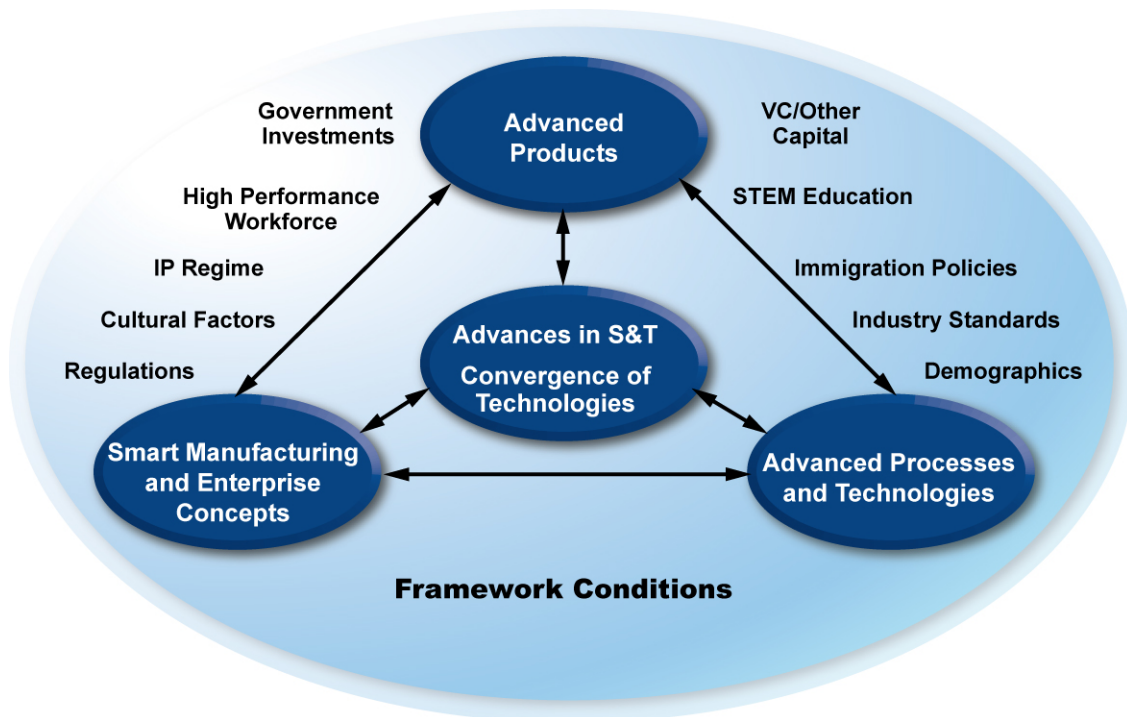


Figure 2. Advanced manufacturing is a multifaceted concept.

There is increasing convergence between manufacturing and services. With manufacturers integrating new “smart” service business models enabled through embedded software, wireless connectivity, and online services, there is now less of a distinction between the two sectors than before. Customers are demanding connected product “experiences” rather than just a product, and service companies such as Amazon have entered the realm of manufacturing (with its Kindle electronic reader).

Advanced processes and production technologies are often needed to produce advanced products and vice versa (Wang 2007). For example, “growing” an integrated circuit or a biomedical sensor requires advanced functionality and complexity, which requires new approaches to manufacturing at the micro scale and the nano scale (Parviz 2007). Similarly, simulation tools can be used not only for making production processes more efficient, but also for addressing model life-cycle issues for green manufacturing.

Key framework conditions that set the stage for advances in manufacturing include government investments, availability of a high-performance workforce, intellectual property (IP) regimes (national patent systems), cultural factors, and regulations (Zhou et al. 2009; Kessler, Mittlestadt, and Russell 2007). Also critical to manufacturing are capital, especially early stage venture capital (VC); a workforce knowledgeable in science, technology, engineering, and mathematics (STEM) disciplines; immigration policies; and industry standards. Demographics play a role: emerging economies tend to have younger populations, and more advanced economies are aging rapidly. These factors are relevant in a globalized marketplace, where national policies drive firm-level decision-making around investment levels in R&D, training, and location of research and manufacturing facilities.

Advanced Manufacturing is not a static entity; rather, it is a moving frontier. What was considered advanced decades ago (pocket-sized personal digital assistants) is now traditional, and what is advanced today (portable high-density lithium-ion batteries) will be considered mainstream in the future.

D. Overview of Report

The next chapter of this report describes five converging trends in advanced manufacturing:

- Ubiquitous role of information technology
- Reliance on modeling and simulation in the manufacturing process
- Acceleration of innovation in supply-chain management
- Move toward the ability to change manufacturing systems rapidly (what the literature calls rapid changeability) in response to customer needs and external impediments
- Acceptance and support of sustainable manufacturing

Chapter 3 (and Appendix C) describes the selection criteria for each technology area presented and outlines the current state of global developments, near- and long-term trends, and science and technology advances and policy changes needed to

accelerate advanced manufacturing. Appendixes F through I supplement the chapter for each of the four technology areas selected for in-depth examination:

- Semiconductors
- Advanced materials with a focus on integrated computational materials engineering
- Additive manufacturing
- Biomanufacturing with a focus on synthetic biology

Chapter 4 discusses enabling factors that affect advanced manufacturing success. The chapter is supplemented by Appendix E, which describes these factors for six countries (Brazil, China, Germany, Japan, Korea, and the United Kingdom).

Chapter 5 contains scenarios that predict what advanced manufacturing will look like in 10 and 20 years in the United States relative to other countries.

The following appendixes supplement the materials in this report:

- Appendix A lists the experts we interviewed by technology area.
- Appendix B presents the definitions we reviewed and used as the foundation to the comprehensive definition of advanced manufacturing presented in this report.
- Appendix C provides a description of the methods and resources used to examine public global investments in manufacturing-related R&D.
- Appendix D presents an analysis of publications from Web of Science that was the basis of keyword analyses to identify emerging trends in microelectronics.
- Appendix E looks at the innovation policies of six countries, because innovation and advances in manufacturing are closely linked.
- Appendixes F through I present case studies for the four technology areas we focused on in this report (semiconductors, advanced materials with a focus on integrated computational materials engineering, additive manufacturing, and biomanufacturing with a focus synthetic biology).

2. Converging Trends in Advanced Manufacturing

Over the past few decades, manufacturing has gone from a highly labor-intensive set of mechanical processes to an increasingly sophisticated set of information-technology-intensive processes. This trend will continue to accelerate as advances in manufacturing are made.

Several broad trends that are changing the face of manufacturing globally are beginning to converge. We consulted experts from academia, government, and industry to identify the broad trends that define these future changes. (See Appendix A for the list of experts interviewed.) They identified five large-scale trends applicable to the manufacturing sector:

- Ubiquitous role of information technology
- Reliance on modeling and simulation in the manufacturing process
- Acceleration of innovation in supply-chain management
- Move toward rapid changeability of manufacturing in response to customer needs and external impediments
- Acceptance and support of sustainable manufacturing

These trends allow for tighter integration of R&D and production, mass customization, increased automation, and focus on environmental concerns. These trends are not mutually exclusive.

This chapter examines these five trends independently and then discusses how their convergence accelerates the emergence of advanced manufacturing enterprises that leverage the trends to their business advantage. Finally, we explain how these trends contributed to the selection of the four technologies that exemplify how advanced manufacturing will change over the coming years.

A. Information Technology

The first major trend in advanced manufacturing is the increased use of information technology. Numerous examples of information technology exist in the domain of manufacturing, including its support of digital-control systems, asset-management software, computer-aided design (CAD), energy information systems, and integrated sensing—see sidebar on the next page for an example (SMLC 2011).

Real-Time Energy-Management Solutions

Many manufacturing facilities are beginning to move toward real-time management of energy use, one of the larger resource expenditures for these companies. Despite the proliferation of real-time energy-management solutions for commercial buildings, sometimes known as energy information systems (Granderson et al. 2009), tools for manufacturing facilities are somewhat less developed, perhaps because the degree of variability between factories is greater than that between different buildings.

The use of information technology not only speeds up overall productivity in the factory by increasing communication speed and efficiency, it also maintains quality by better controlling processes (Iorio 2011; Industrial College of the Armed Forces 2010). In recent years, the tasks that can be monitored and controlled with information technology are increasing in number as well as complexity; these increases are enabling high-speed production with increasing accuracy (Isermann 2011; Mekid, Pruschek, and Hernandez 2009).

The greater use of information technology in manufacturing links the design stage of an individual component to the larger assembly manufacturing system to the use of manufactured products (Iorio 2011). *The use of computer-enabled technologies improves communications that enable both “smart manufacturing” in the factory and “smart supply-chain design”— sending the right products to the right suppliers* (Sanders 2011). The ease of communication is also leading to increasing volumes of data that must be appropriately managed. *The growth of fields such as data mining and informatics is evidence of the increasing concern about appropriate management of high volumes of data.*

Alongside the growing use of information technology is concern over cybersecurity, or the secure collection, transmission, and storage of data (NRC 2007). There has been a significant increase in targeted attacks on large and geographically dispersed networks of businesses and government and military sectors. Often leveraging social engineering and malware, the attacks seek to maintain a persistent presence in the victim’s network and infiltrate organizational networks to extract sensitive information (Villeneuve 2011). The recent demonstration of the Stuxnet distributed denial-of-service attacks is evidence of the possibility of malicious misuse of information or cyber-attacks (Chen 2010). Such attacks emphasize the need for carefully considering such threats as the role of information technology grows.

Sophisticated automation and robotics have the power to democratize manufacturing industries, starting at the lower end of the value chain, but increasingly moving toward complex decision-making roles. Contract manufacturing firms that specialize in mass production of technology products and product components are using robots to push back against rising wages and to increase competitiveness (Yee and Jim 2011). (See sidebar on the next page.)

IT Will Transform Factory Work

Brooks (2012) is professor emeritus of robotics at MIT and founder of the manufacturing start-up, Heartland Robotics. In his recent commentary about the role of information technology in advanced manufacturing, he explains how it will transform factory work:

Thirty years ago, most office workers could not control information flow. They received paper memos and reports printed from mainframe computers. Distributing your own memo was a multiperson process; changing a printout took weeks and a dozen people. The PC changed all that. By the economic boom years of the late 1990s, any individual office worker could produce memos and automate simple tasks, using tools such as e-mail and spreadsheets.

The same democratization of information flow and automation has yet to come to manufacturing. By analogy, our current industrial systems and robots are mainframes, and advanced-manufacturing innovation is concentrated on supercomputers. But the building blocks needed to create the PCs of manufacturing abound; these will be the robotics and automation tools for the masses. We can create tools for ordinary workers, with intuitive interfaces, extensive use of vision and other sensors, and even the Web-based distribution mechanisms of the IT industry.

It was hard to imagine secretaries becoming “programmers” in 1980, and it is hard to conceive of ordinary U.S. factory workers becoming manufacturing engineers. But people who once would have been called secretaries now routinely use spreadsheets, typeset publications, and move money globally. We need to create the tools to similarly empower our factory workers.

B. Modeling and Simulation

The second major trend in advanced manufacturing is the use of modeling and simulation across the product life cycle, which may include the development of products, processes, plants, or supply chains. In contrast to information and technology, which primarily drives speed, efficiency, and quality control in production, modeling and simulation approaches are frequently used to move quickly from the design to production stage (see sidebar “Simulation Models—Toyota’s Central R&D Labs”).

Employing modeling and simulation during the product-development phase allows designs to ensure manufacturing efficiency while decreasing risk from the start by reducing the need for expensive testing and prototyping (Sanders 2011). Further down the product-development line, process-modeling tools also compress the time to market for new products by streamlining the handoff between design and manufacturing divisions of a company (Melkote 2011). In the previous two decades, modeling and simulation approaches have focused primarily on analyses early in the design process, but modeling and simulation tools for later in the development cycle are now being emphasized (National Defense Industrial Association 2011).

Simulation-based approaches for manufacturing offer the potential to optimize design and supply-chain architectures. Simulations minimize risk by incorporating manufacturing considerations into the early phases of conceptual and preliminary designs, where the flexibility exists to pursue alternatives. Currently, most manufacturability problems are uncovered as the designs are being built and tested for the first time, which can lead to significant cost and schedule overruns (Sanders et al. 2010). At this point, it is extremely expensive and often impossible to change the design to improve the yield and manufacturability characteristics (Sanders 2011).

Simulation Models

Toyota's Central R&D Labs have developed several simulation models to predict structural responses of Toyota automobile frames to impacts, noise, wind, and other factors to assess the resistance levels of its auto bodies. (Deshmukh 2009).

Autodesk, a California-based multinational firm, uses a model known as ETO, or engineer to order (Simonite 2011), as an alternative to the traditional approach to producing "high-volume, low-cost outsourced production," sometimes referred to as the "tyranny of bulk" (Sarma 2011). Using this model, customers are allowed to specify the characteristics of the products they want to purchase using a list of general rules, rather than a catalogue or list of already-made products.

Procter & Gamble utilizes several modeling and simulation programs to design efficient factory and production line layouts, ensuring that the logistics associated with one production line do not interfere with another (Siemens 2011).

Simulation-based methods for engineering design and analysis have been in development for over 40 years, and they have fundamentally changed the way products are designed (Glutzer et al. 2009). Specific examples include finite-element analysis for solids and computational fluid dynamics for modeling how fluids move in a designed component (Sanders 2011). Unfortunately, limited attention has been directed at developing comparable manufacturing design and analysis capabilities, and as a result, there is a significant gap in the system-engineering tool kit that can be used to optimize producibility.

C. Innovation of Global Supply-Chain Management

The third major trend in advanced manufacturing is the management of complex global supply chains. Over the past two decades, several trends have led to more complicated supply chains, among them increasing demand for high-technology goods, globalization, decreasing logistics and communication costs, and the growth of e-commerce (Macher and Mowery 2008). The management of these supply chains is enabled by advances in information technology, such as enterprise resource planning software and radio frequency identification (RFID) technology in logistics (Angeles 2009; Zelbst et al. 2010).

As supply chains have globalized and become more complex, business executives have become more concerned with the associated risks (Kouvelis, Chambers, and Wang

2006). Security of these global supply chains may become increasingly problematic because the majority of attention and funding for our transportation security has gone to airport and passenger security (Macher and Mowery 2008). Other factors, such as political interruptions, weather calamities, and labor strikes, may be even more important. Within the broader trends of decreasing inventory and mass customization, supply-chain disruptions can become a much more serious issue (Macher and Mowery 2008). Potential security issues include disruptions and presence of counterfeit or inferior goods (McKnight 2011).

Before the convergence of information technology and globalization, logistics service providers primarily moved goods from one location to another for fixed fees. Today, they work directly with purchasers, service integrators, and consultants to achieve flexible logistics solutions for enterprise resource planning (Sarma 2011; Zelbst et al. 2010).

Innovative supply-chain management reduces the time to fulfill customer orders (see sidebar “The Kiva Warehouse Automation System”). For example, while a typical product might be manufactured in a day or two, passing that product through supply and distribution chains often takes a month or two. Thus, improving the organization and structure of the supply chain can matter more than increasing efficiency within the factory (Suri 2011). If manufacturing begins to move toward more distributed, decentralized production, supply-chain management and innovation will matter even more (Sarma 2011).

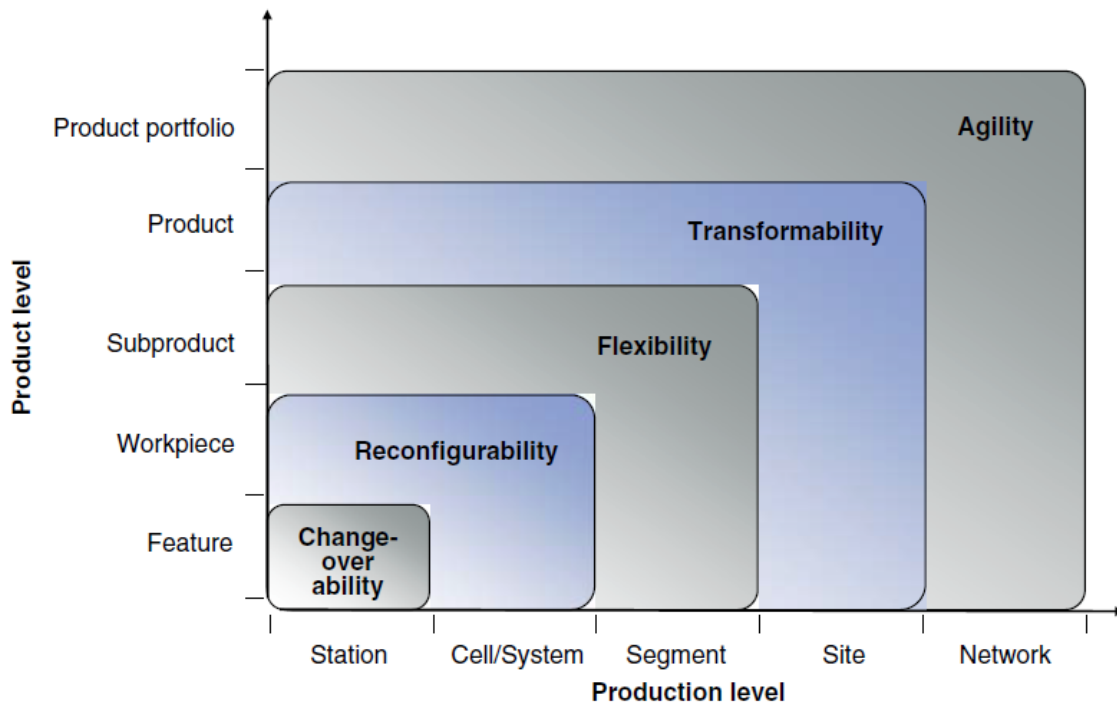
The Kiva Warehouse Automation System

The Kiva warehouse automation system, designed by MIT graduates and students, integrates multiple warehouse functions into one system, from inventory storage to quality control and order fulfillment (D'Andrea and Wurman 2008). The Kiva system uses autonomous robots, mobile shelving units, and integrated control software to fill orders placed at major retailers at any time of day or night. It can handle products of all sizes and shapes and move them to operators when needed.

While RFIDs have been widely used in retail (Karaer and Lee 2007) and assembly environments (Gaukler and Hausman 2008; Gaukler and Seifert 2007), there is a growing body of work examining their use in obtaining lead-time information that can help model and adapt to supply-chain uncertainties (Kouvelis and Li 2008; Burke, Carrillo, and Vakharia 2009). Walmart is an example of a company that is beginning to employ similar approaches that combine RFIDs, IT advances, data mining, low-cost sensors, and robotics to track items in the supply chain and obtain continuous feedback (Bonvillian 2011).

D. Changeability of Manufacturing

A fourth trend is the move toward rapid changeability of manufacturing to meet customer needs and respond to external impediments (Wiendahl et al. 2007). Here, “changeability” is used as an overarching term that encompasses the terms that typically describe existing paradigms of changing production capacity. Among these terms are “flexibility” (Buzacott and Yao 1986; Sethi and Sethi 1990), “reconfigurability” (Mehrabi, Ulsoy, and Koren 2000), “transformability” (Jovane, Koren, and Boer 2003; Nyhuis, Heinen, and Brieke 2007), and “agility” (Gould 1997). The hierarchy of these terms, shown in Figure 3 and defined in the sidebar “Definition: Changeability of Manufacturing,” was proposed by Wiendahl et al. (2007) to distinguish among the changes that take place at different factory levels.



Source: Wiendahl et al. (2007).

Figure 3. Schematic of changeability at various product and factory production levels.

The product hierarchy, beginning with the highest level on the ordinate includes the entire product portfolio offered by a company. Moving down the y-axis, the portfolio is reduced to its smaller constituents, beginning with products, then subproducts, workpieces, and ultimately down to individual features. Similarly, the production-level hierarchy at its highest level along the abscissa is the network, which includes the entire geographically separated production enterprise linked through the supply chain. Moving down the hierarchy presents smaller and smaller production units from site level (i.e.,

factory), to segment level (e.g., facilities for assembly, quality measurement, or packing), to cell or system level (a working area) that produces workpieces and the stations that affect feature-level changes.

Definition: Changeability of Manufacturing

Changeover ability designates the operative ability of a single machine or workstation to perform particular operations on a known work piece or subassembly at any desired moment with minimal effort and delay.

Reconfigurability describes the operative ability of a manufacturing or assembly system to switch with minimal effort and delay to a particular family of work pieces or subassemblies through the addition or removal of functional elements.

Flexibility refers to the tactical ability of an entire production and logistics area to switch with reasonably little time and effort to new – although similar – families of components by changing manufacturing processes, material flows and logistical functions.

Transformability indicates the tactical ability of an entire factory structure to switch to another product family. This calls for structural interventions in the production and logistics systems, in the structure and facilities of the buildings, in the organization structure and process, and in the area of personnel.

Agility means the strategic ability of an entire company to open up new markets, to develop the requisite products and services, and to build up necessary manufacturing capacity.

Source: Wiendahl et al. (2007).

What emerges from these corresponding classes of products and production is a hierarchy of changeability that can be disaggregated into five classes, each subsumed by the next highest level: changeover ability, reconfigurability, flexibility, transformability, and agility (Wiendahl et al. 2007).

Regardless of the term used, growing globalization, shortened product and technology life cycles, ever-changing customer demand, and market dynamics are requiring consideration of a comprehensive view of product or production adjustments when made anywhere in the manufacturing system (Wiendahl et al. 2007; Owen et al. 2011; AlGeddawy and ElMaraghy 2009).

Changeability is furthered by advances in information and technology, as well as modeling and simulation, that help tailor manufacturing systems for goals such as mass customization (Qiao, Lu, and McLean 2006). Achieving truly flexible manufacturing facilities requires advanced processing machines capable of rapidly changing to new designs and new materials, which not only shorten product-development cycles but also make facilities more robust against supply-chain disruptions (Ehmann 2011). Adaptive machines are able to physically move to change the order of operations or internally

adjust to deal with changes. Such machines could possibly even predict where changes will show up by learning (Iorio 2011). These changes in turn will dictate the development of new types of manufacturing processes and how we approach the design of products, since now products must be not only producible but also customizable (Ehmann 2011). *Changeability can also assist design engineers by reducing some of the constraints on their work as more types of design and materials are possible in production* (Iorio 2011).

Increasing changeability in manufacturing could also signal a trend toward decentralized production for some product types. For example, we can imagine downloading digital blueprints for simple devices, customizing the design using simple software, and then fabricating it at a local Kinko's-like facility. Such distributed manufacturing could be made accessible to large masses even in remote areas (Ehmann 2011). For example, Zara is a Spanish retail store that had adopted an advanced integrated manufacturing system that allows it to respond rapidly to the fast-changing fashion demands of consumers. It has tightened its supply-chain management so that the consumer “pulls” the design. Zara uses state-of-the-art IT and distribution systems to collect data daily on trends so they can quickly turn out new designs. Zara keeps costs down by using existing materials in stock and through the use of an automated distribution system that has over 200 kilometers of underground tracking and optical reading devices (Mukherjee et al. 2009).

E. Acceptance and Support of Sustainable Manufacturing

One final trend is the emergence of the concept of sustainable manufacturing, or the application of sustainable development to the manufacturing sector. While there are varying definitions used in the literature, the International Trade Administration (ITA) of the U.S. Department of Commerce succinctly defines sustainable manufacturing as “the creation of manufactured products that use processes that are non-polluting, conserve energy and natural resources, and are economically sound and safe for employees, communities, and consumers” (ITA 2011).

Several factors have drawn sustainability to the forefront of manufacturing. The first is increasing costs for materials and energy and, perhaps in the future, water (Weitzman 2011; Dornfeld 2010). Manufacturers have always been concerned with uncertain energy and material input costs, but recently some of these costs have increased at extremely rapid rates. IT-based solutions for reducing waste and resource use are growing in popularity and represent one convergence of trends. Companies are also increasingly pursuing sustainability for marketing or brand-recognition reasons (Economist Intelligence Unit 2008) (see sidebar “Sustainability at Ford and Lockheed Martin”). Finally, concerns about supply-chain disruptions due to material shortages that could impose extreme costs, such as in the case of rare-earth elements, are weighing heavily on many manufacturers (Iorio 2011; Humphries 2010).

Sustainability at Ford and Lockheed Martin

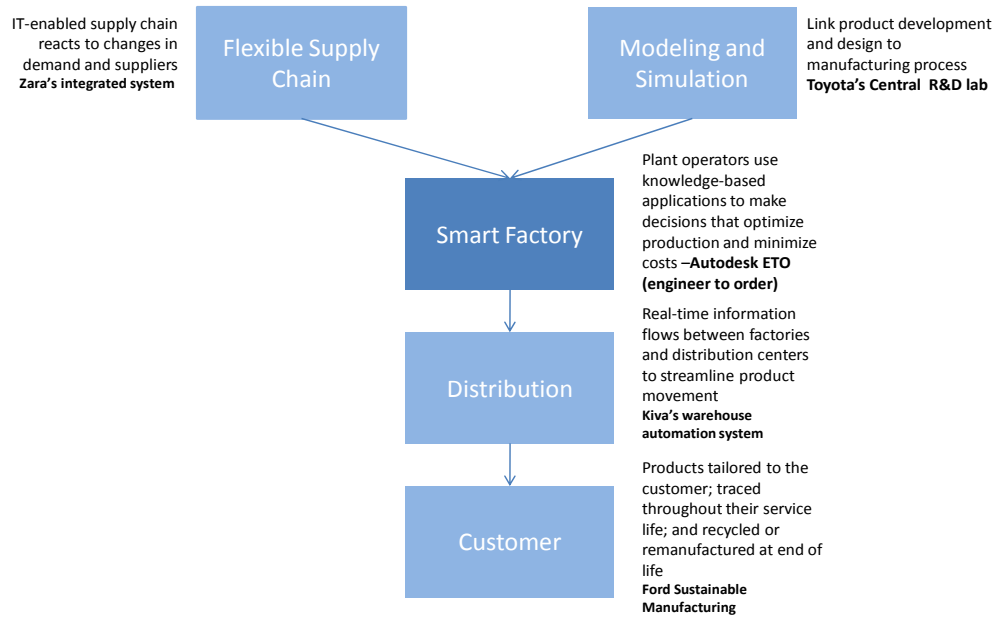
Ford Motor Company has adopted sustainable manufacturing as a company mandate, initiated at its Dearborn, Michigan, Ford Rouge Center, on the premise that “The companies that make the high-quality products and services that consumers really value—and do so in ways that limit harm to the environment and maximize benefits to society—will be preferred in the market place” (Clute 2008). The Ford Rouge Center has been transformed into a sustainable manufacturing center where Ford pilots sustainability projects and then replicates successes at other Ford facilities. Ford is using sustainable materials such as soy foam or recycled materials in creating the car seats. Through adoption of sustainable manufacturing and related processes, Ford has achieved a company-wide 30% energy reduction and 39% carbon reduction from 2000 to 2007. Ford identified many barriers to implementing sustainable manufacturing, such as lack of incentives, the incremental construction and retrofit costs, the limitations in product selection, and the difficulty in quantifying cost savings.

Lockheed Martin’s Go Green program, launched in 2008, has established targets to reduce carbon emissions, water consumption, and waste to landfills by 2012, which has already saved over \$3.3 million (Rachuri et al. 2011).

F. Enterprise-Level Concept of Advanced Manufacturing

Each of these trends reinforces or enables the others, such that they begin to converge to form an enterprise-level concept of advanced manufacturing. The Smart Manufacturing Leadership Coalition (SMLC) has described the convergence of these trends as “smart manufacturing” (SMLC 2011), a term that captures different dimensions of the trends discussed above. Here, we refer to an advanced manufacturing enterprise to describe a firm that takes advantage of each of these trends in combination to create innovative business opportunities.

One previous definition of an advanced manufacturing enterprise is the “intensified application of advanced intelligence systems to enable rapid manufacturing of new products, dynamic response to product demand, and real-time optimization of manufacturing production and supply-chain networks (SMLC 2011).” This idea is represented by a *Smart Factory* that relies on interoperable systems; multi-scale dynamic modeling and simulation; intelligent automation; scalable, multilevel cyber security; and networked sensors. Such enterprises utilize data and information throughout the entire product life cycle with the goal of creating flexible manufacturing processes that respond rapidly to changes in demand at low cost to the firm, as well as to the environment. These processes facilitate the flow of information across all business functions inside the enterprise and manage the connections to suppliers, customers, and other stakeholders outside the enterprise. Figure 4 summarizes the concept.



Source: Adapted from SMLC (2011).

Figure 4. Advanced manufacturing enterprise concepts.

The advanced manufacturing enterprise begins with modeling and simulation to minimize the time needed from product conception to delivery. Information technology such as enterprise resource planning software plans an agile supply chain capable of rapidly responding to both upstream changes such as resource prices and downstream changes such as demand. The smart factory utilizes sophisticated applications to optimize production efficiency and quality control. Forward distribution is also tracked and optimized to deliver products tailored to the final consumer, perhaps even via mass-customization concepts.

3. Emerging Trends in Four Technology Areas

Advanced manufacturing is driven by advances in science and technology that occur in university or industrial laboratories, on factory and shop floors, or at business schools. Both incremental advances and breakthrough advances in traditional and emerging sectors are important for the future of manufacturing. We broadly define advanced manufacturing as manufacturing that builds on and encompasses the use of science, engineering, and information technologies, along with high-precision tools and methods integrated with a high-performance workforce and innovative business or organizational models, to improve existing or create entirely new materials, products, and processes. In this chapter, we describe these trends in four technology areas:

- Semiconductors
- Advanced materials, with a focus on integrated computational materials engineering.
- Additive manufacturing.
- Biomanufacturing, with a focus on synthetic biology.

In the following sections, we give the criteria for selecting the technology areas. We then highlight the key findings for each of the four technology areas, including scenarios in 2030, and barriers to achieving these scenarios. Appendixes H–I presented the detailed case studies for each area.

A. Representative Technologies

We used five criteria as a guide to select technology areas that illustrate how the landscape of advanced manufacturing will change over the coming 20 years. A technology area was selected if it met at least three of the criteria.

1. Criteria for Selection

a. Technology Follows Broader Trends

One of the main goals of the case studies is to examine the possible influence of trends discussed and their convergence into enterprise-level advanced manufacturing; thus, the first criterion was that the case study should be representative of these broader

trends. But because many emerging technologies met this criterion, additional criteria were needed.

b. Potential to Be a Platform Technology

The second criteria for having a potentially high impact on future manufacturing is the ability of a technology or process to act as a platform upon which other technologies or processes can be built. A platform technology is an enabling technology that is a combination of equipment, methods, and other technologies that has the potential to lead to leaps in performance and capabilities of users.¹

This criterion is similar to the idea of key enabling technologies (KETs) examined by the EU. These strengthen industrial and innovation capacity in pursuit of addressing societal and economic challenges (Commission of the European Communities 2009). Implied by this definition is also a high potential for growth, not just in scientific research but also in development (and ultimately deployment) of useful products.

c. National Security

The third criterion is criticality to national security, which was added due to the inherent link between manufacturing and national security noted by many authors (Ezell and Atkinson 2011; National Defense University 2009). We interpret the concept of national security to broadly include military, economic, energy, environmental, political, and societal security issues. Manufacturing and advances in manufacturing are critical to national security for many reasons: to ensure a ready supply of goods and services for defense and commercial needs at reasonable prices, ensure supply-chain integrity, provide employment and economic-growth opportunities, and maintain low-cost and reliable sources of energy and information technology systems (Ezell and Atkinson 2011).

d. The Role of Enabling Factors

The fourth criterion encompasses the role of enabling factors, such as intellectual-property rights and protections. These enabling factors are drivers of innovation but also subject to policy intervention, such as the amount of government investment in R&D, regulations, immigration policies, and the quality of education. Policy-related factors may enable or challenge advances in manufacturing.

¹ Definition adapted from terminology used to describe advances in hardware and software. See <http://www.businessdictionary.com/definition/platform.html>.

e. High Level of Global R&D investment in Science and Technology

The fifth criterion also served as a way to capture any other factors unrelated to the first four criteria. These other factors include culture (such as attitudes toward manufacturing education and workforce), demographic composition (such as an aging population), industry standards, availability of a highly skilled workforce, and accessibility of venture capital and other financing.

The fifth criterion focused on identifying technologies with a high potential for future impact on global manufacturing. Since this criterion is not easily measured, we use a high level of current R&D investment in science and technologies in selected major manufacturing countries as a rough indicator. We chose areas that have the potential to benefit advanced manufacturing as a proxy. While having a high level of investment does not necessarily imply a technology that will be critical to the future, it does suggest that global governments and markets have determined the technology to have a high probability of commercial success.

Using publicly available documents and websites, we identified 36 programs and initiatives in the regions and countries of interest. (See Appendix C for a more detailed description of the methodology used). Table 1 summarizes the types of technologies funded by leading countries in advanced manufacturing. Note that this is not a comprehensive review of all public investments across technology areas, but was meant to provide a high level overview of emerging trends.

Based on this limited search, China funds research in all areas in Table 1, except for “standards” and “general manufacturing.” The European Union funds research in the broad areas listed in the table, but has more gaps in specific areas than China. Other countries fund R&D in areas of their relative manufacturing strengths, such as Japan’s and Taiwan’s funding of information and communication technology (ICT) development. Because the dollar amounts are only approximations of the level of investments, they are represented by Xs for presentation in Table 1.

Table 1. Significant public investments in manufacturing-related R&D.

Manufacturing Technology R&D		EU	Germany	UK	China	Japan	Korea	Taiwan	Brazil
National R&D (public + private) (2008) \$M		294,222	81,849	40,096	120,613	148,719	43,906	20,537	NA
% of National R&D that is public (2008) \$M		46%	33%	55%	28%	22%	27%	30%	NA
Approx. National Manufacturing R&D (public + private) (2008) \$M		261,832	72,839	29,602	104,479	133,746	38,881	19,054	NA
Advanced materials and applications	Li-ion and thin film battery technology				X	X	X	X	
	Photovoltaics		X		X	X		X	X
	Materials research for green manufacturing	X			X	X		X	
	Fuel-cell technology	X			X		X	X	
	Materials modeling and simulation	X		X	X			X	
	Nanomaterials and applications	X	X	X	X			X	X
ICTs (microelectronics and photonics)	Printed electronics/roll-to-roll processes				X			X	
	CMOS and related microelectronics	X	X	X	X	X		X	
	MEMS and sensor devices	X			X			X	X
	Advanced telecom devices				X			X	
	Displays incl. OLEDs (organic light-emitting diodes)				X	X	X	X	
	Low power electronics		X		X	X		X	X
	Nanoelectronics	X	X	X	X	X	X	X	X
Transportation and avionics	Alternately fueled vehicles	X		X					X
	Space avionics				X	X			X
Biomanufacturing					X			X	X
General (all-inclusive) manufacturing		X							X
Standards		X							X
Tooling and equipment	High-performance machinery		X		X			X	
	Modular machines	X	X		X				
	Rapid Tooling				X				
	Robotics				X	X			
Digital Manufacturing	Mass customization (additive manufacturing)	X			X				
	Digital design technology		X		X				
	Network-centric production	X			X				

Manufacturing Technology R&D		EU	Germany	UK	China	Japan	Korea	Taiwan	Brazil
Process control and monitoring	Sensing and detection		X		X	X		X	
	Process control technologies	X	X		X				
Enterprise-level convergence	Energy efficiency	X			X				X
	Flexible manufacturing	X	X		X			X	
	System modeling and simulation	X			X			X	

Sources: For rows 2–4, Total GERD (public + private) from Main Science and Technology Indicators. GERD: Gross Expenditure Domestic on R&D (million current dollars (\$), corrected using purchasing power parity, http://stats.oecd.org/BrandedView.aspx?oeed_bv_id=strd-data-en&doi=data-00182-en and STAN R-D Expenditure in Industry (ISIC Rev. 3) ANBERD ed2009 (not PPP) http://stats.oecd.org/Index.aspx?DataSetCode=ANBERD2011_REV3.

2. Technology Choices

While the applicability of these criteria to each technology will be discussed more in each the following chapters, here we preview the technologies in terms of their applicability to the trends in advanced manufacturing:

- *Semiconductors*—Semiconductors are highly critical for information technology and defense technologies. In addition, as Table 1 shows, almost all countries presented here have invested in R&D for microelectronics. Finally, very few technologies serve as a platform for further innovation more than semiconductors.
- *Advanced materials and integrated computational materials engineering (ICME)*—Advanced materials are essential building blocks in everything from household products to defense-critical applications. The importance of advanced materials is evident from the high level of global R&D investment in them. A relatively new approach to integrating materials information with computational tools, engineering performance analysis and process simulation holds significant promise for optimizing materials, manufacturing processes, and products. ICME tools enable the development of designer materials for specific applications (Brinson 2011).
- *Additive manufacturing*—Additive manufacturing is a processing technology that exhibits relatively low levels of global R&D today but has the potential to become a platform to shift the entire manufacturing enterprise toward more distributed production models. Creating products via additive processes rather than traditional subtractive ones allows inherent flexibility and customization, contributes to sustainability through decreased materials waste, and presents new and interesting digital supply-chain possibilities for product design and delivery.
- *Biomanufacturing with a focus on synthetic biology*—Synthetic biology is a subset of biomanufacturing and is the primary area of focus in this report. This multidisciplinary emerging technology area introduces engineering approaches

of modularization, modeling, and a rational and iterative design cycle² to molecular biology to exercise precise control over cell functions and products (Koide, Pang, and Baliga 2009). The production of pharmaceuticals via biological techniques also has the potential to simplify the supply chain and produce pharmaceutical products flexibly, possibly to the point of creating custom drugs and vaccines. Further, biotechnology could potentially serve as a platform technology for many types of biological and nonbiological products.

B. Trends in Semiconductor-Manufacturing Technology³

1. Introduction

Today, semiconductor manufacturing is a mature industry generating \$300 billion in revenue, with manufacturing facilities in over 20 countries. It is the cornerstone of a global information technology (IT) economy, supporting a \$2 trillion market in electronic products and an estimated \$6 trillion in service industries across sectors ranging from health care and transportation to banking and defense (Zhang and van Roosmalen 2009).

Today's information processing needs are powered by silicon-based integrated circuits (ICs). The silicon microprocessor, containing more than 2 billion transistors, each functioning and interconnected by a well-defined, hierarchical wiring scheme, and measuring in nanometers, is one of the more complex pieces of machinery ever manufactured.

The complexity of the process and the product is the direct result of doubling the number of transistors on the chip every 2 years, as the industry has done since the 1970s. This doubling phenomenon is referred to as Moore's law. The result is a better cost-to-performance ratio of products that rely on the transistors, which has introduced an exponential growth of the semiconductor market. This has been accomplished by scaling down transistor devices to ever-smaller dimensions, following rules for transistor scaling that were established by Dennard et al (1999).⁴ By scaling the transistor, the manufacturer was able to simultaneously improve performance, reduce power, and lower the cost of the product. But the escalating cost of R&D in recent years has motivated industry collaboration through consortia and various R&D partnerships (Mims 2010).

² See *Stanford Encyclopedia of Philosophy*, "Rationalism vs. Empiricism," First published Thu Aug 19, 2004; substantive revision Wed Aug 6, 2008; <http://plato.stanford.edu/entries/rationalism-empiricism/>.

³ See Appendix F for additional information on this technology area.

⁴ Dennard's finding was that if the transistor's lithographic dimensions and the operating voltage were scaled down by the same factor, the resulting device would be faster, less expensive, and more power efficient.

By 2025, advances in mobile computing and cloud connectivity combined with the growth of sensor networks will set the vision for a cyber-physical world with ubiquitous computing capability (PCAST 2010a; Sha et al. 2009). The sensors may be embedded into objects or cover complete walls, leading to trillions of connected devices; the networked sensor systems enable real-time data processing on wireless computing devices, creating intelligent and adaptive cyber environments for emerging applications such as autonomous transportation systems (Rabaey 2008).

2. Global Developments

In semiconducting manufacturing technology development, the high cost of research and innovation has resulted in companies becoming risk-averse in making R&D investments, and there has been increasing consolidation within the industry. Further, as semiconductors have become commoditized, development and innovation in manufacturing have increasingly shifted to Southeast Asian countries that rely on economies of scale to drive out competition. Precompetitive R&D will be increasingly conducted mostly in partnerships or consortia, which allows manufacturing leaders (Taiwan Semiconductor and Samsung) who are now collaborators to begin to become R&D leaders.

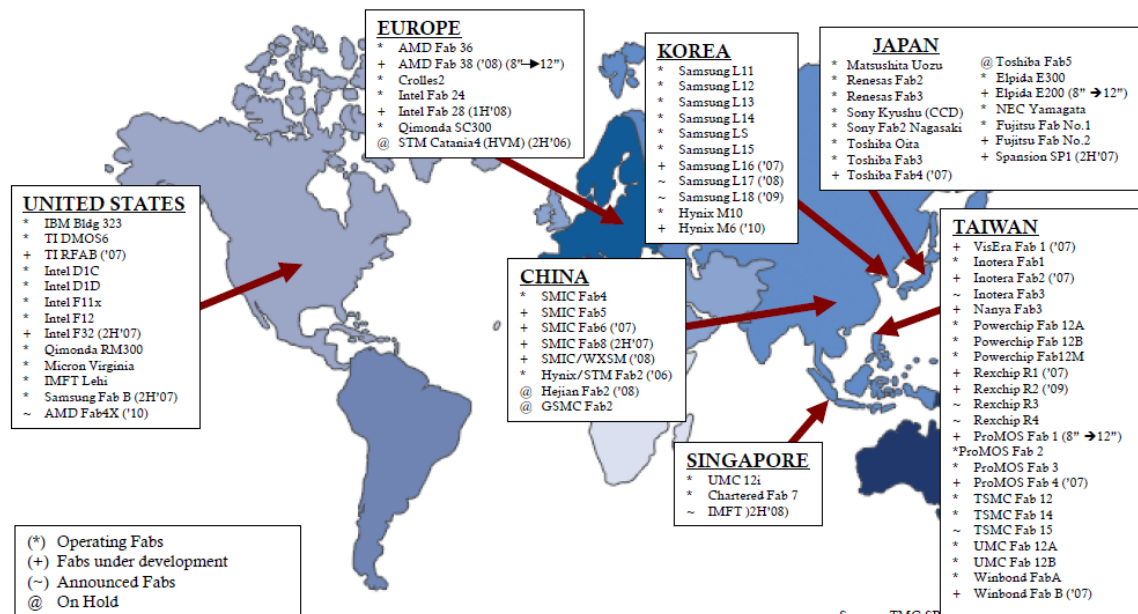
The growth of semiconductor-fabrication facilities is expected to continue at a much higher rate largely outside the United States than within. The attrition of the U.S. semiconductor manufacturing base will continue to affect research in infrastructural areas such as materials and instrumentation, modeling and simulation, and tooling.

Figure 5 shows the geographic distribution of semiconductor manufacturing facilities worldwide, including both foundries and IDM manufacturing plants. While China leads in the number of planned fabrication facilities (five), overall manufacturing capacity is highest in Japan, closely followed by Taiwan. Taiwan is home to two of the leading foundries, TSMC and UMC, as well as a host of memory-chip vendors and other IC makers. Based on forecasts, by mid-2011 Taiwan will have surpassed Japan to have more semiconductor capacity than any other region in the world, producing nearly 25% of projected global capacity. South Korea, meanwhile, has the highest concentration of fabrication facilities at the cutting edge of manufacturing (IC Insights 2011).

Internationally, Japan, Taiwan, and Korea have an established position in the industry, with China slowly ramping up its foundry capabilities. While Intel and AMD, two U.S. companies, have led manufacturing in the microprocessor market, Japan has historically led in memory products. In recent years, however, Korea (Samsung) has taken the lead in this, as well as in the mobile devices industry. China is rapidly emerging, aided by government policies that attract foreign manufacturers to set up foundries in the country. Its semiconductor industry accounted for 11% of the global industry in 2009, up from 2% in 2000 (Chitkara 2010). The European Union strength is

its formation of public-private partnerships in France, Germany, and across the EU. The EU also has coordinated efforts through Framework programs by funding specific areas of interest, such as Future and Emerging Technologies (FET) Flagship (Future and Emerging Technologies (FET) 2011) programs (set to receive up to €1 billion over 10 years). In general, the EU is investing in long-term research programs that mirror those in the United States.

The result of this increasing global spread of the manufacturing supply chain is a decrease in the control over the system; electronic products manufactured overseas, both defense and consumer goods, may be susceptible to tampering and counterfeiting.



Source: Lemnios (2011).

Note: The United States has 13 fabrication facilities, whereas Southeast Asia has more than 60.

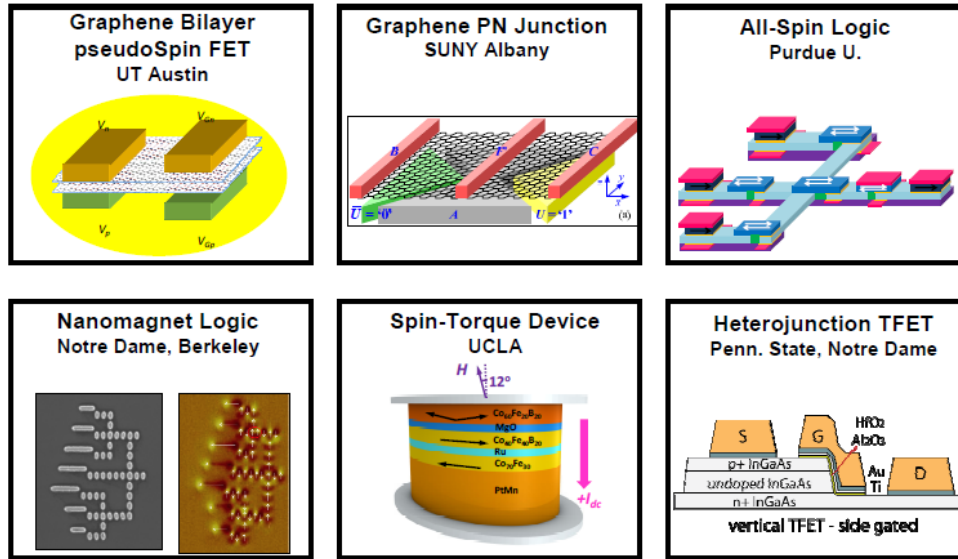
**Figure 5. Global spread of semiconductor industry:
Leading-edge foundries have moved to Asia over the past two decades.**

3. Near- and Long-Term Trends

Three complementary paths or trends are expected to occur in the semiconductors industry over the next 20 years. These technology developments are not sequential but occur in parallel, with advances in one feeding into the other areas. Each of these trajectories as described by the International Technology Roadmap for Semiconductors (ITRS) will require substantial changes in design, architectures, system-integration models, and process technologies. (Each of the trajectories was informed by bibliometrics searches of keywords—see Appendix D.)

The three trends are described below:

- *“More Moore”*—The inherent difficulties of continued linear scaling have required the industry to focus on “equivalent scaling” pathways to extend the CMOS process to its anticipated limit by 2020. Multicore processor design along with the insertion of new materials into the CMOS process such as high-K dielectrics in the place of silicon dioxide insulator will drive transistor performance improvements in the near term.
- *Functional diversification or “More-than-Moore” or “System-on-Chip”*—This trajectory involves incorporating dissimilar components directly onto the silicon platform (also called system-on-chip, or SoC) (ITRS 2010a). Starting with the integration of the processor, memory, and communication components, microelectromechanical systems (MEMS) sensors and microfluidic components could eventually be integrated. A compact system with multiple functionalities will drive the proliferation of integrated circuits in improved communications, bio-electronics and transportation (Trew 2011). It also opens up possibilities for mass customization of chips with innovative and desired functionality.
- *Beyond CMOS*—this trajectory includes research on emerging devices and materials, focused on a “new switch” that will initially supplement the functioning of the current CMOS and eventually supplant it. The Nanotechnology Research Initiative (NRI), in partnership with the NSF, has funded 5 collaborative research programs at over 35 universities with a goal of demonstrating novel computing devices capable of replacing the CMOS transistor as a logic switch by the 2020 time frame. (Figure 6 shows the emerging device concepts being developed by the NRI-funded programs.) The focus is on exploring new physics and new materials to fabricate devices that will use new state variables (such as electron spin, magnetic spin, molecular state, etc.) enabling information-processing capability substantially beyond that attainable by “ultimately scaled CMOS.” Examples of Beyond CMOS include the development of carbon-based nano-electronics, tunneling devices, spin-based devices, ferromagnetic logic, atomic switches, and nanoelectromechanical system (NEMS) switches (Welser 2011)(ITRS 2010, Chen 2011a, Welser 2011).



Source: Theis (2010).

Figure 6. Selected post-CMOS devices.

4. Science and Technology Advances and Policies Needed

In the long term, advances in the semiconductor industry will be driven by the exponentially increasing costs of manufacturing and the drive toward low-power devices.⁵ This has motivated the exploration of lower cost fabrication methods such as nanoscale self-assembly processes for patterning, as well as new materials and mechanisms for charge transfer devices. Complementary advances will be needed in chip design, chip architecture, and design-automation technology. A gradual shift toward bottom-up manufacturing methods may be seen; however, such a shift is anticipated to be decades away.

External factors have played an important role in the globalization of the semiconductor industry. Government policy in the form of tax laws, intellectual-property protection, procurement, and access to capital and markets has helped countries like Korea and Taiwan quickly become world leaders in the semiconductor industry; China is now following suit. A trained, skilled workforce continues to be a critical factor for countries to move up the R&D and manufacturing value chain. Increasing automation can also be a big equalizer, along with vertical disintegration of technologies. Potential barriers to achieving this scenario include possible lack of infrastructural research in developing new materials databases and multi-scale simulation tools. Integrated computational materials engineering (ICME) and similar programs may help with this. In addition, new computing architectures, circuit designs, and devices expected to evolve in

⁵ Rising manufacturing costs have led to the formulation of “Moore’s second law,” which is that the capital cost of a semiconductor-fabrication facility also increases exponentially over time.

the 20 year time frame need fundamentally different modeling and simulation tools to support development, from multi-scale modeling to quantum- and parallel-computing architectures. Currently, simulation capability lags the pace of technology development. See the following sidebar for other challenges and barriers to technology advances.

Challenges and Barriers

Technology Challenges

- Rapid shrinking of the domestic supplier base because of increasing consolidation as well as off-shoring of manufacturing services has negative impacts on U.S. advancement in manufacturing technology and infrastructural areas (materials, instrumentation, tooling, etc.).
- High level of investment needed in R&D makes technology developers highly risk-averse and is a big barrier to technology-based innovation.
- Simulation capability lags the pace of technology development. New IC design and architectures need new and multi-scale simulation tools to support development.
- Globally linked manufacturing and enterprise systems and migration to cloud sharing also highlight the increasing need for cybersecurity and robustness of IT infrastructures.

Barriers Due to Factors External to Technology

- Tax breaks and other direct incentives offered by foreign governments (China, Korea, Taiwan) to offset manufacturing capital costs for semiconductor companies makes the United States uncompetitive as a location to set up new manufacturing activities.
- Erosion of manufacturing base in the United States is slowly causing a diversion of the technology talent pool to overseas opportunities.
- Global dispersion of the semiconductor manufacturing supply chain has led to a loss of control over the ecosystem, creating vulnerabilities for the defense electronics industry.
- Sustained funding for long-term, high-risk research is a barrier to continued U.S. leadership in this field.

Countries that will lead in 2030 will have invested in cyber and physical infrastructure to take advantage of the anticipated growth in wireless technologies over the next 10–20 years. These developments encompass the pervasive use of embedded microprocessors in sensor networks, automated transportation systems, medical devices, and other areas that require this technology.

The sidebar on the next page, “*Zizhu chuangxin* (Indigenous Innovation): China’s Rising Capabilities in Microelectronics Technology,” describes China’s indigenous innovation policy in the context of microelectronics technology. China’s National Medium and Long-term Plan for Development of Science and Technology (2006–2020) (Cao, Suttmeier, and Simon 2006), known as “MLP” in the West, is a blueprint to turn China’s economy into a technology powerhouse and reduce its reliance on foreign technology in core infrastructure systems such as banking and telecom. In particular, *China aims to achieve global preeminence in electronics, and it has accelerated funding in this area since 2001 even as U.S. funding has declined substantially.*

Zizhu Chuangxin (Indigenous Innovation): China's Rising Capabilities in Microelectronics Technology

China's policy of "zizhu chuangxin" (many refer to it as indigenous innovation) focuses on building on its internal innovation and production capabilities to reduce dependence on foreign technology. *Making incremental improvements to produce technology appropriate for market needs and shortening the time to market are viewed as more critical by officials and entrepreneurs than the novelty and allure of high technology* (Breznitz and Murphree 2011). In many of its microelectronics research programs, China has tactically chosen to focus on areas that will give them a long-term advantage over foreign competition.

China's rapid ascent in computing-hardware capabilities and the migration of integrated circuit manufacturing to Asia in the last two decades has led to *China's increasing control over the global electronics supply chain*. China represents a vast untapped market for chip makers: in August 2011, China, for the first time, became the world's largest PC market, surpassing the United States (Fletcher 2011). Moreover, as China moves upstream in the electronics supply chain, it poses an increasing threat to the security of the U.S. defense electronics industry.

Three examples follow.

(1) The Loongson microprocessor

The Chinese Academy of Sciences' Institute of Computing Technology has created a microprocessor brand named Loongson ("dragon chip") with the goal of achieving "CPU independence" for China by creating inexpensive, usable CPUs that can dominate the domestic PC market by 2020.

- The Loongson processor has been developed using an older, more power-efficient (MIPS) technology, rather than Intel's dominant x86 "Wintel" architecture (Herman 2011).
- The Loongson chips are described as "power sipping" in comparison to U.S.-made processors, a huge advantage in embedded and battery powered devices (such as cell phones and laptops) in the future. That is, the Loongson chip focuses on power efficiency rather than performance.

When the Loongson chips do hit the market in China, they will be a lot slower than an Intel or AMD chip, but "enough for most office and other purposes" and about half the cost. (Fletcher 2009). According to China's Ministry of Industry and Information (MIIT), Chinese-made integrated circuits will meet 27% of Chinese domestic demand by 2015, up from 8% in 2010, and this trend will grow. (Alspector 2011)

(2) The Tianhe-A1 supercomputer

In October 2010, China's Tianhe-A1 supercomputer, developed by the National Supercomputer Center in Tianjin, was clocked as the world's fastest by a factor of 50%, leaping ahead of Cray's Jaguar located at the Oak Ridge National Lab (Ricker 2010).

- The Tianhe-1A made substantial leap in processing speed not by using faster processors, but by strategically addressing the biggest bottleneck in supercomputing systems—interconnects that allow flow of information from one processor to another.
- While Infineon (a European company) leads the market in interconnect technology, the Chinese team spent years designing its own proprietary interconnect technology (named Galaxy), which is reportedly twice as fast as Infineon's (Herman 2010; Merritt 2010).

(3) The Kylin operating system

The Kylin operating system, developed by China's National University of Defense Technology (NUDT), is being installed on government, military, and financial systems with the goal to make Beijing's networks impenetrable to U.S. military and intelligence agencies (Coleman 2009).

- The Kylin is reported to be a version of FreeBSD, an open-source version of the UNIX operating system, but with extra layers of security to make it impenetrable (Alspector 2011). (China built the Kylin using the FreeBSD operating system as starting point, in violation of the open-source license.)

C. Trends in Advanced Materials and Integrated Computational Materials Engineering (ICME)⁶

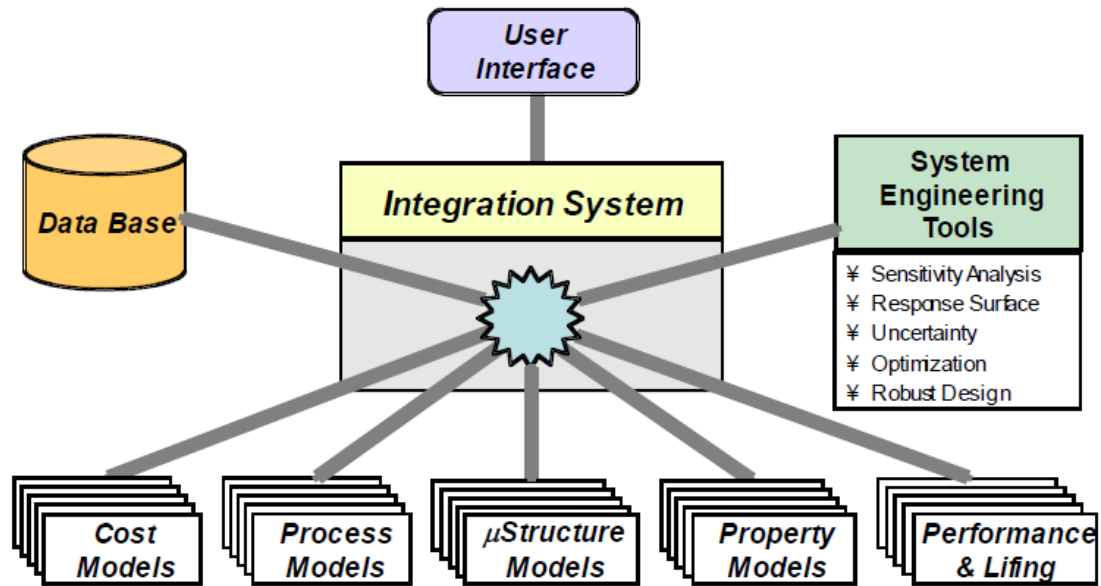
1. Introduction

From the discovery of iron and bronze in ancient times to later achievements in fuels and macromolecular synthetics, advanced materials have a history of opening new vistas of technology. To this day, they continue to provide the essential building blocks of numerous end-use products, ranging from household items to critical defense applications. They remain a gateway to new manufacturing technologies as well as a driver of novel processes that can herald the development of revolutionary products.

Advanced materials possess new or innovative internal structures, which yield superior properties and facilitate disruptive or transformative changes in manufactured products (Mathaudhu 2011; Moskowitz 2009). From this perspective, the field is constantly evolving and leading to manufactured products with an unprecedented range of applications. During discussions with experts for this study, one of the most prevalent issues identified regarding advanced materials in the United States is the need to accelerate the development and application of new materials to maintain a competitive advantage in technological development.

One area that holds enormous potential for growth and for accelerating the insertion of materials into products is integrated computational materials engineering (ICME). As defined by a recent report of the National Research Council (2008b), ICME is “the integration of materials information, captured in computational tools, with engineering product performance analysis and manufacturing-process simulation.” As depicted in the example ICME system shown in Figure 7, this holistic approach combines multiple models with a database of information and systems analysis tools, which are available to the user via a graphical interface. Although currently in a nascent stage of development, ICME has already demonstrated an ability to loosen the constraints on product design and manufacturing processes by linking our understanding of materials phenomena from the quantum to the bulk scale.

⁶ See Appendix G for additional information on this technology area.



Source: Air Force Research Laboratory (Cowles and Backman 2010).

Figure 7. Depiction of components of example ICME system.

2. Integrated Computational Materials Engineering: Successes and Global Development

a. Recent ICME Successes

While ICME is a young field, a few examples of its use in commercial applications already exist and have demonstrated a return on investment ranging from 3:1 to 9:1 (NRC 2008a). One of the earliest implementations of ICME concepts was with the DARPA accelerated insertion of materials (AIM) program that began in 2001. This initiative was created with the goal of establishing new frameworks for the integration of tools that would quickly and cheaply develop and qualify new materials and processes.⁷ Through this work, Pratt & Whitney demonstrated the ability to reduce forging weight by 21% while concurrently increasing disk burst speed by 19% (NRC 2008a). At the same time, GE showed their approach could accelerate disk alloy development by 50% (Cowles and Backman 2010). Following the initial DARPA AIM investment, the ONR/DARPA “D3D” Digital Structure Consortium was formed with the purpose of higher fidelity microstructural characterization and simulation to support the AIM methodology (Olson 2011; Kuehmann and Olson 2009). Ultimately, these two phases of AIM led to the first

⁷ A more thorough treatment of the results of the DARPA-AIM program is reported in a study produced by the National Materials Advisory Board, “Accelerating Technology Transition: Bridging the Valley of Death for Materials and Processes in Defense Systems,” available at: http://www.nap.edu/catalog.php?record_id=11108.

fully computationally designed and qualified material, the Ferrium S53 landing gear steel, which reached flight in December 2010 (Kuehmann and Olson 2011).

A handful of other companies including Livermore Software Technology Corporation, ESI Group, Naval Surface Warfare Center, Knolls Atomic Power Laboratory (Lockheed Martin Corporation), Toyota Central R&D Labs, QuesTek, and Boeing have also employed ICME concepts of integrating materials, component design and manufacturing processes as described in the National Materials Advisory Board Study with the National Research Council (2008a). Both major manufacturers and small companies, usually with government sponsorship, have utilized an ICME approach and realized its benefits.

b. Global Development

The United States is currently among the leaders in developing ICME tools, but other countries, especially select countries in the EU, are also making significant investments in this area (Allison 2011; Pollock 2011). Within the EU, the Germany and the United Kingdom are the dominant countries in ICME concepts, especially relating to automotive and defense applications (Anonymous on ICME 2011; Pollock 2011), with Sweden also making significant contributions (Pollock 2011). France also has ongoing work in the direction that meets its needs in nuclear and defense applications (Pollock 2011).

One indication of China's growing interest in ICME occurred in 2009, when the Chinese Academy of Sciences selected the 2008 National Academies report on ICME as one of a few priority reports to be translated into Chinese (Allison 2011). Whereas China's computational capabilities have been increasing along with the number of ICME related publications (LeSar 2011), their potential remains unclear (Pollock 2011).

One expert noted that market forces may begin to prompt other countries, such as Singapore and South Korea, to begin to explore ICME for consumer electronics (Anonymous 1 on Advanced Materials 2011). In Japan, there is also interest in ICME, along with computational materials science strengths (Pollock 2011). Australia has emerging work in ICME, especially on lightweighting and 3-D aspects (Pollock 2011).

3. Near- and Long-Term Trends

Experts were consulted to identify potential breakthroughs and advances in ICME that may occur in the next 5–10 years (near term) and up to 20 years or more (long term). Breakthroughs included both evolutionary and revolutionary progress that could likely occur over the prescribed time lines. Early ICME successes are likely to remain in structural materials applications, including metal-alloy systems, which are already well characterized. Later advancements may include work in electronics or biomaterials.

One likely near-term evolutionary breakthrough from ICME is that it will enable the design engineer to delay specific material choices to later stages of the product development process, thus optimizing the final materials chosen. A key part of this approach will be a suite of tools to connect, enhance, and even replace what is already in existence, allowing people to start with new materials or dramatically different derivative materials and still develop a product from start to finish in 1 to 5 years instead of 10–30 years as is often the present case. Such capabilities will become an imperative for companies to develop materials as fast as design (Pollock 2011). The following sidebar details other potential breakthroughs.

Potential Long-Term Breakthroughs

Design

- Sustainability-driven designs may lead to reductions in the use of environmentally unfriendly materials and processes.
- Supply-chain risks could lead to the use of ICME for facilitating the substitution of critical materials such as rare-earth elements with materials that are more readily available via a domestic or diversified supply chain.
- The line between mechanical and materials design will become blurred as designing components and manufacturing will be done using almost entirely computationally based methods.
- Combining ICME with nondestructive evaluation will greatly enhance the ability to predict a material's lifetime.
- All the materials, mechanical, and systems data will be available to the designer, resulting in unsurpassed freedom of design.
- Materials' discoveries will likely be catalyzed once ICME tools are available.

Technology

- Supercomputing power will inevitably increase over the next 20 years, leading to increasingly complex models with improved accuracy (i.e., ability to predict uncertainty).
- The advent of additive printing technology for doing direct writing of materials will take advantage of ICME to optimize the materials and processes involved (LeSar 2011).

Supply Chain

- The deployment of ICME into industrial applications will necessitate a better understanding of the relationships among sectors, their requirements, and the roles of individual suppliers.

Access to material properties data will also improve over time as a unified material taxonomy is created and populated with modeling and experimental results. Curated resources will help fill in key information gaps, as well as ensure high standards of data quality, which are an imperative to promoting integration of such databases with computational tools.

There is still significant room for progress in materials modeling, which may be aided by breakthroughs in the area of informatics that allow information to be extracted

from increasingly complex models and simulations (LeSar 2011). Informatics could also lead to extracting old sources of information that can be applied in new ways.

In the longer term, broader societal trends in sustainability will likely lead to greater application of concepts such as materials substitution and recycling, which will be aided by ICME tools. Moreover, the degrees of freedom allowed in designing materials will continue to grow, thus necessitating the use of ICME tools to better assess the tradeoffs of various material choices (LeSar 2011). This will also lead to the blurring of the line between mechanical and materials design. Designing components and manufacturing will be done using almost entirely computationally based methods as disciplines begin to speak the same language (Anonymous on ICME 2011). The inevitable increase in supercomputing power over the next 20 years will also aid this approach.

Combining ICME with nondestructive evaluation will greatly enhance the ability to predict a materials lifetime (i.e., prognosis). ICME will provide more robust designs by more accurately predicting lifetime constraints, thus reducing the unnecessary use of time and resources simply because parts are replaced earlier than necessary (LeSar 2011).

In 20 years there will likely be a shift in the way materials specifications or design codes are applied. All the data will be available to the designer, resulting in unsurpassed freedom of design. This is in contrast to today, where specifications and materials that are constant with one set of properties are used (Anonymous on ICME 2011).

The deployment of ICME into industrial applications requires the involvement of numerous organizations that stretch from academia through industry to provide and maintain tools that cross a variety of disciplines (Furrer and Schirra 2011; Pollock 2011). While the supply chain may ultimately take on a number of different forms, its establishment will require a better understanding of the relationships among sectors, their requirements, and the roles of individual suppliers (Furrer and Schirra 2011). What the supply chain ultimately looks like will depend on whether there is a large, coordinated effort that will benefit from government investment or whether it is accomplished through small grants to universities and other organizations (Pollock 2011).

4. Science and Technology Advances and Policies Needed

Despite recent advancement of ICME concepts, a variety of technical, cultural, and other barriers may inhibit progress in the field. Major efforts will be needed to overcome some of these challenges, which require both evolutionary and revolutionary advances across many disciplines.

In addition to funding research to address fundamental materials behavior and modeling, agencies need to support integrated efforts of researchers across disciplines in a sustained manner that allows the ICME infrastructure to develop. Unifying, agreed-upon taxonomies should be created at the international scale to lay the groundwork for

successful coordination and linking of databases. Managing such databases will also be required to ensure integrity of information. And rapid experimentation and three-dimensional characterization techniques need to be developed to effectively evaluate and screen properties.

Educational efforts will also be required to teach this holistic, systems-based materials-development approach to the existing generation of workers, as well as to students across various disciplines. Culturally, ICME signals a change in the way regulatory agencies may oversee materials development; their early involvement is therefore needed to ensure appropriate verification and validation of models to an acceptable fidelity. The sidebar “Barriers to Development of ICME” details other challenges to developing ICME.

Barriers to Development of ICME

Technology Challenges

- Materials behavior involves complex physical phenomena spanning widely different length and time scales, which is difficult to capture in models.
- Characterizing modeling uncertainty is difficult, especially when determining propagation through various length and time scales in multi-scale models.
- Unifying taxonomies are needed, along with informatics for information extraction.
- Managing data will require sufficient and sustained resources.
- Integration tools, including virtual libraries of material property data that are properly linked, will be a necessary component of the ICME framework.
- Rapid experimentation and three-dimensional characterization techniques are needed to enable rapid evaluation and screening via information such as phase diagrams (Zhao 2006).

Other Challenges

- A primary cultural barrier is education, including that for skilled teachers, trainers, and workers.
- The ability to accurately verify and validate models to the fidelity acceptable to regulatory agencies must be realized.
- Employing ICME methods is expensive, emphasizing a need to settle intellectual-property issues that might prevent companies from investing in it.
- Funding was commonly cited by experts as a barrier to entry.
- There is an inability of funding agencies to support integrated efforts of the right groups of researchers from the various disciplines needed to make ICME successful (LeSar 2011).
- Future limitations may be imposed by export controls or international traffic in arms regulation (ITAR) restrictions.
- Forming the appropriate linkages in the supply chain to advance ICME may be difficult.

D. Trends in Additive Manufacturing⁸

1. Introduction

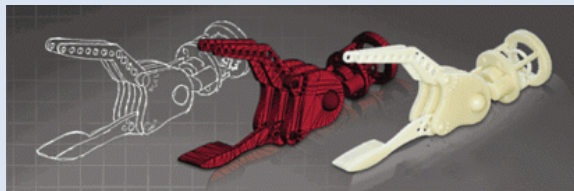
Additive manufacturing describes multiple techniques (see the sidebars “Additive Manufacturing Excels when Parts Are Designed To Be Made Together” and “Selective Additive manufacturing Processes”) in use since the mid-1980s to build solid parts by adding materials in layers. In contrast to the traditional “subtractive processes” that remove material from solid blocks to manufacture goods, additive manufacturing reduces waste because it only uses the materials needed to produce a product. The process also reduces the need to maintain large inventories of component parts because they can be produced using just-in-time or nearly just-in-time processes. With about \$1.2 billion in worldwide sales of systems, materials, and services in 2010, additive manufacturing is a small but rapidly growing industry.

Additive manufacturing, an enabling technology, has the potential to fundamentally change manufacturing. An additive manufacturing machine can produce multiple types of products without retooling. This has the potential to benefit defense industries such as aerospace, which demands a continual lightweighting of components. Additive manufacturing companies are already working with large defense contractors such as Lockheed Martin, Northrop Grumman, and Boeing.

“Additive Manufacturing Excels when Parts Are Designed To Be Made Together”

The original design of the robotic arm in the picture below has many different parts for each component of the hand and joints, requiring joints, pins, and washers to hold it together. Using additive manufacturing techniques, the arm can be made as one unit, while still maintaining the flexibility, accuracy, and strength of the original 15 parts. The robotic arm can be customized to make it smaller or larger or to change another facet.

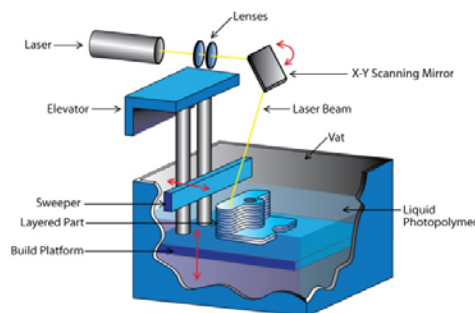
Additive manufacturing enables the producer to design, draw, and produce a consolidated robotic arm in a continuous process. The process can be adjusted to meet customer needs without retooling.



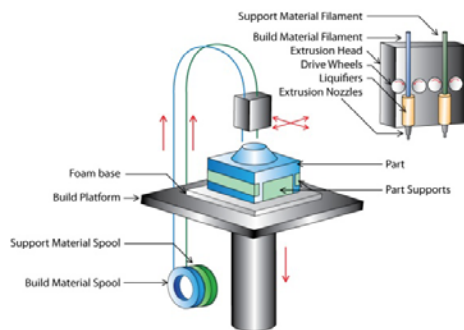
Source: Assembly Automation (2011), <http://www.emeraldinsight.com/journals.htm?issn=0144-5154&volume=31&issue=1&articleid=1907218&show=html>.

⁸ See Appendix H for additional information on this technology area.

Selected Additive Manufacturing Processes



Stereolithography—This process makes use of photo-curable plastic resins that are treated by UV laser to become solid or gel-like and is most often used for prototyping (Hopkinson 2010).



Fused deposition modeling (FDM)—This process uses hot nozzles to extrude polymeric material into position, using one nozzle to extrude support material and a second to extrude the part.

Subtractive Machining:

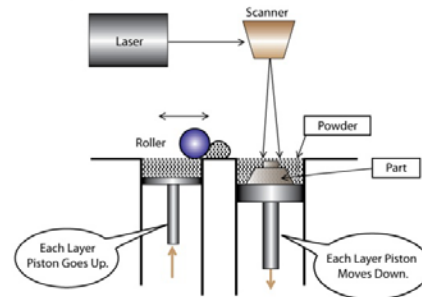


Additive Manufacturing via EBF³:

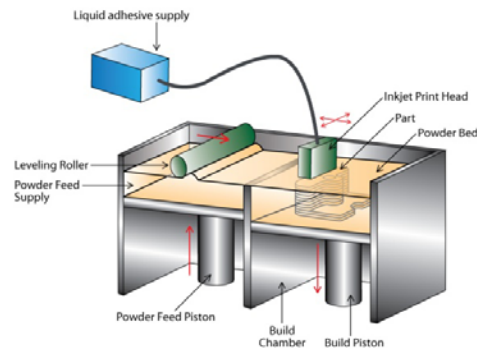


EBF³ saves significant resources over current methods: raw materials, energy, fewer chemicals (cutting fluids), lead time = cost

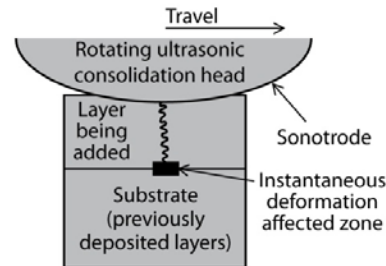
Electron beam melting or e-beam melting (EBM)—This is a process that uses an electron beam in place of a laser to directly melt metal powder into parts. (Arcam, a Swedish manufacturer, has pioneered the use of electron beam melting (Tamingier 2008).)



Powder bed (laser) sintering—Laser sintering fuses together powder from a bed. Originally, laser sintering could produce polymer as well as metallic and ceramic parts (using each type of powder), with binders needed in the case of metal or ceramic powders. Recently, more powerful lasers have been used to directly sinter metal and ceramic without the use of binders (Hopkinson 2010).



Inkjet Deposition (3D Printing)—This process uses an inkjet similar to those found in 2D printers. It works by depositing a binder on a powder bed that joins the powder in each layer without the use of lasers.



Ultrasonic consolidation (UC)—One of the newest additive manufacturing technologies, patented by an American company called Solidica and in development by Solidica and the Edison Welding Institute (Slattery 2011). This process uses metal foils held together under pressure, combined with ultrasonic vibrations that create a weld between layers of foil, which are then machined to the desired shape (Domack and Baughman 2005).

2. Global Developments

The United States is in a strong position to continue as an industry leader in many areas of additive manufacturing, including low- to mid-priced machine manufacture and adoption. In terms of total installed base, the North American region leads with 43% of machines, followed by 30% in Europe, 23% in Asia-Pacific, and the remainder in other areas (Wohlers 2011b).

While several U.S. manufacturers are still successful in the European market, several European manufacturers are now competing well in many market segments. *European companies have a lead in the direct-metal-manufacturing segment of the additive manufacturing market.* Europe also is a leader in direct-metal research:

- The Fraunhofer Institute in Germany, a leader in laser technology, has done significant research on laser-based additive processes.
- Katholieke Universiteit Leuven in Belgium is a world leader in direct-metal additive manufacturing.
- Loughborough University in the United Kingdom is widely recognized for its expertise (Wohlers 2011b; Bourell 2011).

Roughly one quarter of all additive manufacturing machines are estimated to be installed in Asia. Of these, Japan accounts for almost half and China accounts for about one-fourth (Wohlers 2011b). Japan was an early adopter of additive technology, and recently its companies have been relatively unable to sell machines to manufacturers outside of Japan. The situation is similar in China. A large number of Chinese companies now offer additive manufacturing services, mainly for design and prototyping rather than part production. This trend is an example of how earlier stages of product-value chains are moving to Asia. There is some growth in Taiwan and Australia, but like China, the growth is mainly in use rather than in innovation and development (Wohlers 2011b). Currently, there appears to be few Asian companies that have a global presence (and hence none are mentioned in the table below).

Israel has emerged as a global player due to a single company, Objet Geometries, which has sold nearly as many machines as all the European companies combined (Wohlers 2011b).

Representative companies that produce or use additive manufacturing machines and that have a global presence are listed by country:

- **United States**
 - *Stratasys*, which mainly uses Fuse Deposition Modeling (FDM) processes, recently *announced* a partnership with Hewlett-Packard to produce 3D

printers, a move some see representing a watershed moment for the technology due to the capital and brand of HP (Wohlers 2011b).

- *3D Systems*, a major player in the global market for plastics additive manufacturing, has recently made many acquisitions among both equipment manufacturers and service providers, often known as service bureaus in the industry (Wohlers 2011b).

- **Europe**

- The *Swedish company Arcam* is the world leader in the electron beam melting process, which is growing in popularity for direct-metal parts due to its energy efficiency and speed. Arcam has focused primarily on high-value markets, especially titanium alloys for medical and aerospace uses (Wohlers 2011b).
- *EOS* uses primarily laser-based processes for its machines, most of which have the advantage of the flexibility to produce either plastic or metal parts including steel, titanium, aluminum, and cobalt-chrome alloys (Wohlers 2011b).
- *Shapeways*, a Dutch company that recently relocated to New York, uses a network of service bureaus to build parts and ship them directly to consumers. Nearly anything can be designed by customers and shipped to them after manufacturing, within size and material limitations (Wohlers 2011b)

- **Israel**

- *Objet Geometries* utilizes 3-D printing inkjet technology and manufactures several low- to mid-priced systems, some of which fit on a desktop. One of the major selling points of *Objet's* technology is the ability to print in multiple polymeric materials. (Wohlers 2011b).

- **New Zealand**

- *Ponoko* is a New Zealand company where consumers can buy, sell, or trade digital designs (including many free options).

3. Near- and Long-Term Trends

In the near term, (next 5 to 10 years), there will be two broad trends. Consumer machines will continue to drop in price, and industrial machines will continue to get better but stay expensive. Consumer machines produce products that require less complexity and accuracy than those produced by industrial machines. Industrial applications will require process improvements and innovations to accelerate

development of faster, more accurate machines to ensure quality control of products. Some recent technology trends in additive manufacturing include the following:

- *Process Improvements*—Future machines will increasingly utilize hybrid technologies that take advantage of the strengths of several types of additive and subtractive processes.
- *Speed*—The key will be the trade-off between feature size and speed, as one must typically be sacrificed for the other.
- *Quality Control*—Machines will begin to increase quality control and produce parts with higher repeatability.
- *Materials*—Innovations may allow a broader material coverage by additive processes, expanding the current set of materials to include new polymers and potentially even biological materials

Early application areas will be consumer products, medical implants and tools, dental implants, and aerospace. *Consumer machines* will make manufacturing a distributed paradigm (e.g., iTunes for music; sending files by e-mail to a local print shop such as Kinko's) or follow the e-commerce model (e.g., Amazon.com). On the *industrial side*, additive manufacturing will focus on producing high-value components and products, along with those requiring complex internal geometries that cannot be made using traditional manufacturing techniques. Industrial machines will continue to improve, building more types of materials, parts, and eventually whole products with increased speed and precision. *To advance, industrial machines will rely on process improvements, quality control, and development of new materials.*

Additive manufacturing, when fully developed and scalable, will lead to economies-of-scale calculations so mass customization and easy changes in design become possible. The expectation is that by 2030, machines will have improved to the point that they can build whole volumes at once, creating multiple material products quickly and at relatively high precision, directly competing with traditional manufacturing approaches. *Three scenarios are possible:*

- Current trends will accelerate so that additive manufacturing becomes increasingly faster while maintaining an increasingly thinner layer-based approach. This will require significant technical advances in the software and materials.
- There will be a trend away from layer-based and toward volume-based advanced manufacturing—that is, filling a shell rather than layering material to create a product. Very early stage research is underway, but there are currently no known processes for this approach.
- Bio-inspired self-assembly and nanotechnology will be used in the additive manufacturing processes. For example, the German Fraunhofer Institute is

developing new biocompatible materials and a manufacturing process that combines 3-D inkjet printing and a laser-based polymerization technique for cross-linking with precision. The institute notes, “this is a step towards future industrial processing of elastic biomaterials and creation of biofunctional structures for and medical applications.”

- The potential for the United States to compete in these markets will be improved by additive manufacturing techniques as capital and labor costs are leveled and design innovation becomes more important.

4. Science and Technology Advances and Policies Needed

Scientific and technology advances are needed on multiple fronts to address the following challenges to development of additive manufacturing processes and machines (see sidebar “Barriers to Developing Additive Manufacturing”). Currently, additive manufacturing techniques and materials are more expensive and slower than traditional manufacturing for large production runs. In addition, most machines are able to produce small parts, consumer products, and medical components, but not large products. Research is needed to reduce the costs of additive manufacturing materials and processes; to accelerate the speed of the processes; and to scale the capabilities, both in terms of volume produced and size of the product.

Barriers to Developing Additive Manufacturing

- Technical challenges with respect to scaling up size of production runs and ability to produce more than small parts; increasing speed of production; and reducing cost of machines and materials.
- Lack of commercial funding to scale up production of additive manufacturing machines.
- Concerns about cybersecurity and likelihood of theft due to portability of designs and ease of replication.
- Intellectual-property challenges, such as deciding who owns and profits from digital designs.
- Lack of liability and regulation to assess who is responsible for self-manufactured digital designs.
- Lack of Food and Drug Administration, Department of Defense, and other approval processes for use.
- Lack of design tools and educated workforce that can use the tools.

Policy will also play a role in accelerating the development of an additive manufacturing industry. For example, industrial policy should support increased R&D funding for developing new design tools and processes, as well as for developing regulations, standards, and intellectual-property regimes that address issues raised by a shift to additive manufacturing processes. Finally, advances in cybersecurity are needed to address additive manufacturing issues such as theft due to portability of designs and ease of replication.

The sidebar “Additive Manufacturing for Weapons System Spare Parts Production” provides an example of how additive manufacturing could benefit the production of spare parts for weapons systems.

Additive Manufacturing for Weapons System Spare Parts Production

Managing spare parts for military weapons systems is a complicated, time-consuming, and expensive task involving large inventories (GAO 2008). Many military systems, including aircraft, are increasingly being used beyond their designed life expectancy (NRC 1997), and parts that have never been in danger of failure are in need of replacement. Remaking the part via traditional forging, casting, or machining can often take up to 2 years, not including additional time for qualification and delivery (Frazier 2011). These problems not only require billions of dollars to support vast inventories but also necessitate long-term grounding of systems, threatening national security (GAO 2008).

Additive manufacturing has been identified as a potential solution to the spare parts inventory problem. The types of parts most likely to use on-demand additive production in the near term are parts smaller than 1 cubic foot, made of high-value materials, and with relatively low part counts.

Additive manufacturing could potentially allow the production of spare parts on demand, either centrally or in the field:

- Shipping digital designs instead of parts could increase the efficiency of defense logistics and the infrastructure to support them, particularly by reducing inventories kept in the field.
- Less energy would be used to transport, package, and store the spare parts.

This reduction of storage would have a large benefit for space-constrained systems like submarines, which need spare parts in the field. NASA is interested in additive manufacturing for spare parts on space missions for similar reasons (Lipson 2011).

Titanium alloys have been identified as a likely first application area, since they are expensive and difficult to machine and significant material losses occur using traditional subtractive processes. The Navy and Defense Logistics Agency have identified over 300 Ti-6Al-4V alloy parts that have a production lead time of greater than 1 year (Frazier 2011).

Significant barriers exist to achieving the goal of on-demand spare part production in the field:

- First is the need for additive processes to be qualified for use in weapons systems. Testing and certification take time and money, and it is not clear who would pay for such testing. Additive processes have not yet been standardized and may require different testing than traditional approaches since failure mechanisms may be different (Kinsella 2011).
- Second is the need for digital designs of the spare parts. Where these would come from depends on who owns the intellectual property—sometimes this is the military and sometimes not. For out-of-production parts, CAD drawings could theoretically be achieved through reverse-engineering techniques (Frazier 2011).

While these barriers are significant, the benefits of on-demand direct part production are many—decreased part inventories, acquisition costs, and system downtime. Through additive manufacturing, future defense logistics could be made leaner, more energy-efficient, and more secure.

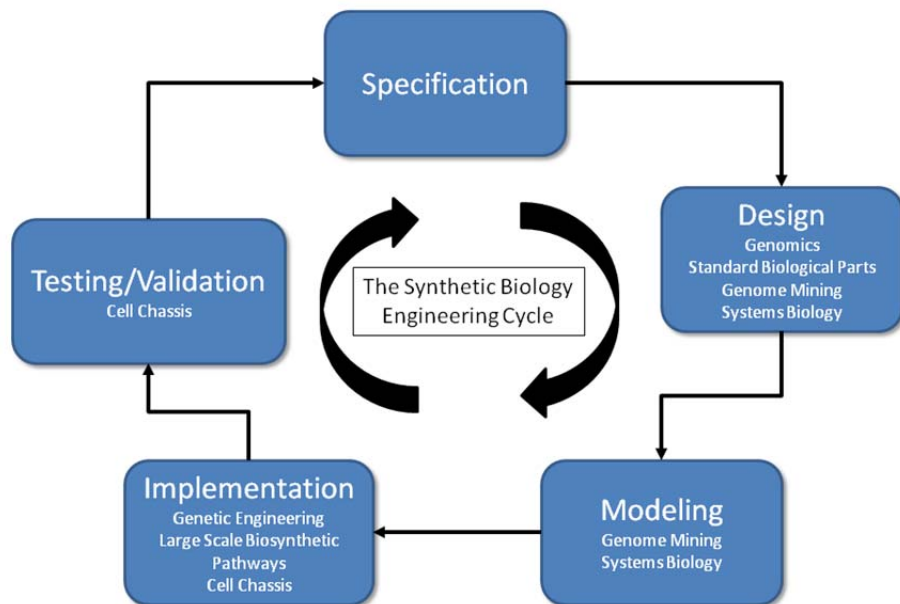
E. Trends in Biomanufacturing with a Focus on Synthetic Biology⁹

1. Introduction

Biomanufacturing harnesses living systems to produce desired products by purifying a natural biological source (e.g., penicillin from mold) or by genetically engineering an organism to produce a product. Biomanufacturing products are generally hampered by a lack of predictability and standardization of the engineering tools. Products have to be specially designed on a case-by-case basis through a mostly trial-by-error procedure.

⁹ See Appendix I for additional information on this technology area.

Synthetic biology is a nascent science and engineering discipline that seeks to develop an engineering design, build, and test cycle to manufacture biological products and systems inexpensively and rapidly (see Figure 8) (Royal Academy of Engineering 2009). Standardization—by developing a toolbox of standard biological parts that might be wired together into a biological genetic circuit that allows control of cell functions and production of products—is key to the discipline. These circuits then regulate a large-scale biosynthetic pathway within cells to develop products. A few proof-of-principle successes have been published by academic laboratories, and a few biotech startups have adopted synthetic biology practices to produce products (Ro 2006). If successful, synthetic biology techniques have the potential to apply to several manufacturing sectors, such as pharmaceuticals, biofuels, environmental sensors, agriculture, biological computing, and materials.



Note: Adapted from The Royal Academy of Engineering synthetic biology report (2009).

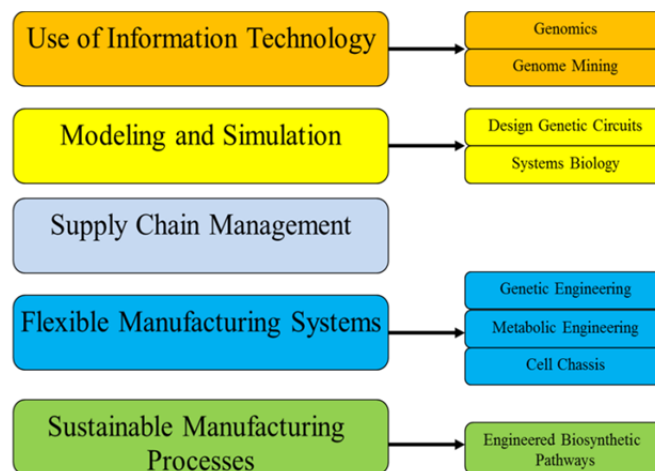
Figure 8. A proposed synthetic-biology engineering cycle.

Today, the state of the art of genetic engineering is more like DNA editing, where DNA sequences for desired products are modestly altered to achieve desired capabilities. Synthetic biology seeks to introduce a rigorous engineering cycle to the process—a relatively new paradigm for genetic engineering for more ambitious engineering of biological systems.

Synthetic biology is not without controversy. The idea of an engineering cycle is a commonplace concept in other disciplines, and some experts we interviewed see an engineering cycle in biology as a necessary and revolutionary concept to unlock vast potential for the production of biofuels, materials, and new biochemistries. But other

experts see this concept as naive and the discipline of synthetic biology as simply an extension of biotechnology and genetic engineering. Regardless of how synthetic biology is defined, the goals, concepts, preliminary experiments, and modest successes associated with it hint that engineering in biology may have future potential to positively affect manufacturing of a broad range of products.

Because of this potential and because synthetic biology’s purported goals and methodologies show qualities similar to those of advanced manufacturing trends, the technology was included in this study (Figure 9). Synthetic biology relies heavily on genomics and systems biology to find appropriate parts for a particular synthesis and design the necessary genetic circuit to control production. Information technology and modeling and simulation techniques are brought to bear on complex biological problems. To standardize the manufacturing of biological products, flexible manufacturing systems are also a goal for synthetic biology. In particular, the idea of producing a bacterial cell with the minimum DNA genome to support life functions is critical. This minimized cell or chassis would be stripped of unnecessary DNA before manufacturing, thus simplifying the engineering problem of producing desired product. Finally, synthesizing products through enzymatic catalysis rather than industrial chemical catalysis is an example of a sustainable manufacturing process—enzymatic transformations tend to be more environmentally friendly than chemical and industrial transformations.



Note: Left—key advanced manufacturing trends identified in this report.
 Right—subdisciplines attributed to synthetic biology that demonstrate the advanced manufacturing trends in synthetic biology.

Figure 9. Synthetic biology and advanced manufacturing trends.

2. Developments in the United States Relative to Other Countries

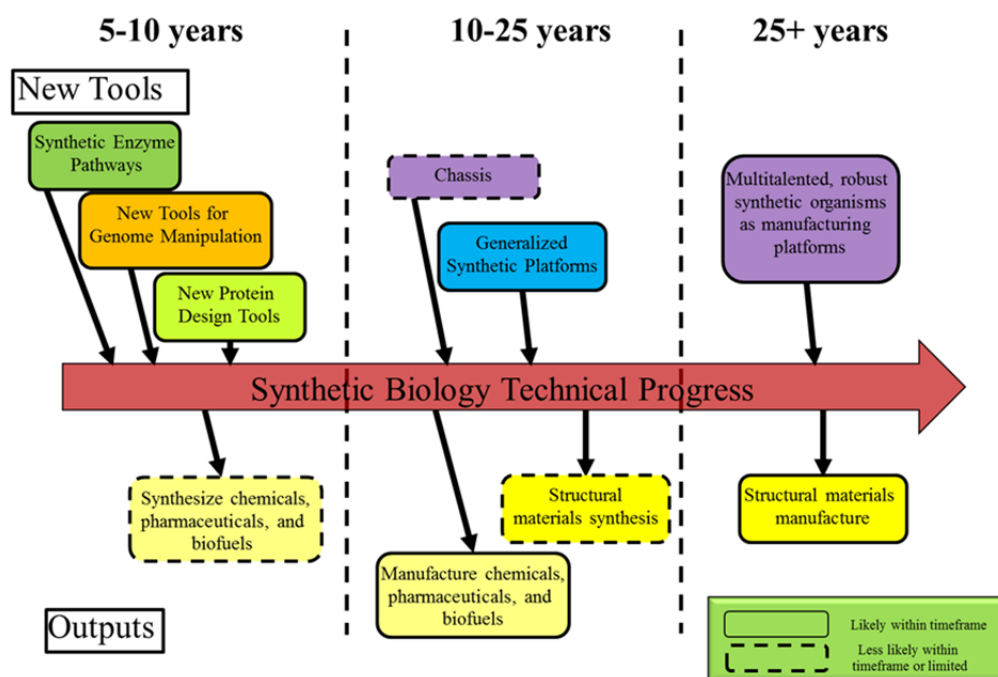
Several governments (led by the United States) have recognized the importance of synthetic biology to national security and are starting to invest in the technology. Although current data are not complete, it is estimated that the U.S. Government funds roughly \$140 million/year in synthetic biology research; the European Union invests roughly one-third to one-quarter of that level (Woodrow Wilson International Center for Scholars, 2010). China has recently developed an interest in synthetic biology with similar research goals as the United States (Pei et al. 2011). But like western countries, it is having trouble with defining the field and assessing its impact. Much biotechnology funding in China is through government programs such as the 863 Program (National High-tech R&D Program), the 973 Program (National Basic Research Program of China), and the National Science Foundation of China (NSFC). Currently, synthetic biology efforts are spread among these three programs, and it is difficult to assess total government investment. For example, 973 Program is funding a 40 million CNY/year (~\$6.4 million/year) program to develop an artificial synthetic cell factory. A dedicated research funding strategy has been proposed in China for synthetic biology, but it has been delayed due to a lack of a consensus definition for the discipline.

3. Near- and Long-Term Trends in Biomanufacturing and Synthetic Biology

Interviewed experts see tool development as the most important development in synthetic biology in the next few years (above red arrow in Figure 10), with some successes likely in manufacturing chemicals and other molecules in biological systems. Synthetic biology will continue to exploit current mature molecular biology tools such as genetic engineering, metabolic engineering, and evolutionary processes to meet synthetic biology goals. At the same time, progress in synthesizing chemicals in modestly engineered biological systems will continue. Some successes in biopharmaceutical development have been achieved (see Appendix I). Work will continue to develop genomic circuits to control communication within and between cells to program them for the manufacture of desired products.

As the tools become more generalized and flexible (10 years out and on), there could be potential to more routinely manufacture chemicals in biological systems. This potential depends on the success of generalizing cells and methodologies and optimizing them for the production of chemicals, pharmaceuticals, and biofuels. Developments in programs to develop synthetic biology chassis, artificial cell factories, or “living foundries” (as one DARPA program is named), should be monitored for progress.¹⁰

¹⁰ DARPA’s Living Foundries Program is part of their Microsystems Technology Office, see http://www.darpa.mil/Our_Work/MTO/Programs/Living_Foundries.aspx.



Notes: New methodologies and tool development are above the red progress arrow, and potential outputs are below the arrow. Dotted lines surrounding tools and outputs indicate less confidence in achieving these goals within the time frame.

Figure 10. Potential advances in biomanufacturing with synthetic biology tools.

The manufacture of structural materials may be more difficult to program in a biological system due to the complexity of three-dimensional structure. This was seen by one expert as a particularly vexing problem for synthetic biology. Perhaps in the far term, when manufacturing in biological systems might be mature, structural materials could be programmable in biological systems.

4. S&T Advances and Policies Needed to Accelerate Development of Biomanufacturing and Synthetic Biology

Many of the barriers that could prevent synthetic biology from becoming a crosscutting manufacturing platform might be technical in nature. The discipline has had a few manufacturing successes to date, and it is currently unknown if synthetic biology can reach its proposed potential. Critics have stated that a lack of fundamental biological knowledge, the complexity of genetic circuits, and wiring those circuits into higher order control elements may prevent synthetic biology from reaching its potential (Kwok 2010).

Even though over 5,000 biological parts have been deposited in the Registry of Standard Biological Parts, many have been uncharacterized or poorly characterized. In addition, assembling parts can lead to unpredictable performance in the resulting circuitry, as well as have unintended effects on the cell in which they have been placed.

The unpredictability of biological parts forces researchers to continue to use a trial-and-error approach, which they ultimately seek to eliminate from their engineering. Work must be done in the field to rigorously characterize parts, circuits, and avoid interactions with the cell chassis. Random fluctuations and noise have yet to be characterized and dealt with in biological circuitry.

Synthetic biology also faces a number of policy issues that have arisen, namely intellectual-property, ethical, biosafety, biosecurity, and societal issues (Royal Academy of Engineering 2009). Since synthetic biology advocates the synthesis of novel microorganisms, there are ethical concerns in humanity's role in developing novel life forms. It is unclear how willing the public would be to accept such research since there already has been much debate about genetically modified organisms. Such debate suggests that there may be even greater resistance to radical modification of organisms and developing novel organisms through synthetic biology. Another concern is that these novel organisms could have unanticipated biosafety issues if accidentally released outside the laboratory. Genetic manipulation of microbes is also a concern of the biosecurity community, which must consider that the technology could be abused by nefarious communities to produce a bioweapon. Finally, issues of intellectual property have to be dealt with so that both innovation and proprietary rights are protected. All these policy issues need to be addressed if synthetic biology is able to meet its technical challenges and produce novel biological systems.

Today, the purported potential of synthetic biology technology is outstripping actual achievements. A deeper study of this technology—with the goal to assess the technical, future potential, national security, safety, economic, and social issues associated with synthetic biology—is necessary. (See sidebar “Challenges for Developing Synthetic Biology Technologies into a Mature Manufacturing Field.”).

Challenges for Developing Synthetic Biology Technologies into a Mature Manufacturing Field

Synthetic biology is an immature field that has a number of challenges (technical and policy) that need to be addressed before it can be realized as a manufacturing technology. According to Luis Serrano, a researcher at the Centre for Genomic Regulation (Barcelona Spain), "We are still like the Wright Brothers, putting pieces of wood and paper together. You fly one thing and it crashes. You try another thing and maybe it flies a bit better" (Kwok 2010).

Technical

- Biological Parts need to be characterized—Parts are currently deposited in registries and not fully characterized, leading to unpredictable results.
- Wiring of circuitry needs to be more predictable—Current technology or systems are unable to predict if parts will work as expected when wired together, even if individual parts are well-characterized.
- Biological parts have to be compatible with host or chassis—Parts can interact negatively with chassis. These host-part interactions are unpredictable with current technology.
- Large genetic circuits are labor intensive to build with current molecular biology technology.
- Higher order genetic control elements need to be developed instead of simple logic gate or control elements—Even though new synthetic biological circuits are developed, their level of complexity has flattened out.
- Noise in genetic circuits needs to be characterized.

Policy

- Ethical—What is humanity's role in developing new life forms?
- Biosafety—Novel organisms can have an unpredictable effect on the environment if released.
- Biosecurity—Synthetic biology is dual-use. The technology could be abused to produce a novel organism that could be used as a bioweapon.
- Societal—Manage public reaction to synthetic biology research and its products.
- Intellectual Property—Proprietary rights need protection while balancing the need for innovation.

4. Enabling Factors to Advanced Manufacturing Success

A. Introduction

Countries established as manufacturing leaders (e.g., Germany, Japan, Korea, and the United Kingdom) and countries whose capabilities have accelerated in the past 20 years (e.g., Brazil and China) exhibit common goals: to strengthen their manufacturing base and to capitalize on emerging technologies developed at home and elsewhere.

In the aftermath of the recent financial crisis, both groups are looking to increase manufacturing as a source of economic growth, exports, and jobs (Manufacturing Institute 2009). Maintaining technological superiority in advanced manufacturing is seen by many as a national security issue, particularly within the defense industrial base (DOD 2010; National Defense University 2009). Some have argued that research and development and innovation flow from manufacturing and production facilities. Thus, countries that fail to attract or maintain vibrant advanced manufacturing sectors risk further decreasing their economic competitiveness (Pisano and Shih 2009; OECD 2011a; Ezell and Atkinson 2011).

Whether the impetus is jobs, innovation strategy, national security, or some other reason, many countries are developing policies that specifically target advanced manufacturing and the broader innovation system that supports advances in manufacturing. This chapter examines the factors that enable the abilities of different countries to compete in this new environment. We first explore the factors that increase a country's manufacturing competitiveness and then provide examples of recent national policies and investments in several countries.

B. Competitiveness

1. Overview

We reviewed the literature that describes why certain regions are more successful in developing an advanced manufacturing sector or attracting foreign investment in advanced manufacturing. A variety of models explain why manufacturing firms are drawn to different geographic areas or countries. In the classical model of a profit-seeking firm, the firm chooses to locate in an area that minimizes the cost to bring products to market and maximizes total revenues in both local and global markets (EOP 2009). Most models attempt to break down the complex location decision into a series of factors. Commonly called "location factors," they express different dimensions of the

attractiveness of a country or region for production. Such factors are specifically related to the costs or market opportunities of firms in that location, and economic models attempt to describe location factors in the cost minimization framework (Hayter 1997).

There is no comprehensive list of location factors, and the importance ascribed to different factors varies depending on the point of view of the modeler, sector, etc. To create as comprehensive a list as possible, we examined three sources of survey data on economic competitiveness for manufacturing investment: the World Investment Prospects Survey (WIPS) from the United Nations Conference on Trade and Development (UNCTAD 2009), the Manufacturing Competitiveness Index (MCI) from the Deloitte Council on Competitiveness (2010), and the Global Competitiveness Index (GCI) from the World Economic Forum (WEF 2011).

Table 2 shows that the sources ascribe varied importance to different categories of factors. For example, Deloitte's Manufacturing Competitiveness Index does not include market size and growth as a potential factor, but does provide a category for energy costs separate from the broader natural resources categories used elsewhere. The UNCTAD World Investment Prospects Survey puts more emphasis on co-location or agglomeration effects than others, but lacks indicators on government or university support for innovation with industry. We grouped similar factors together where possible to create the list in the first column of the table.

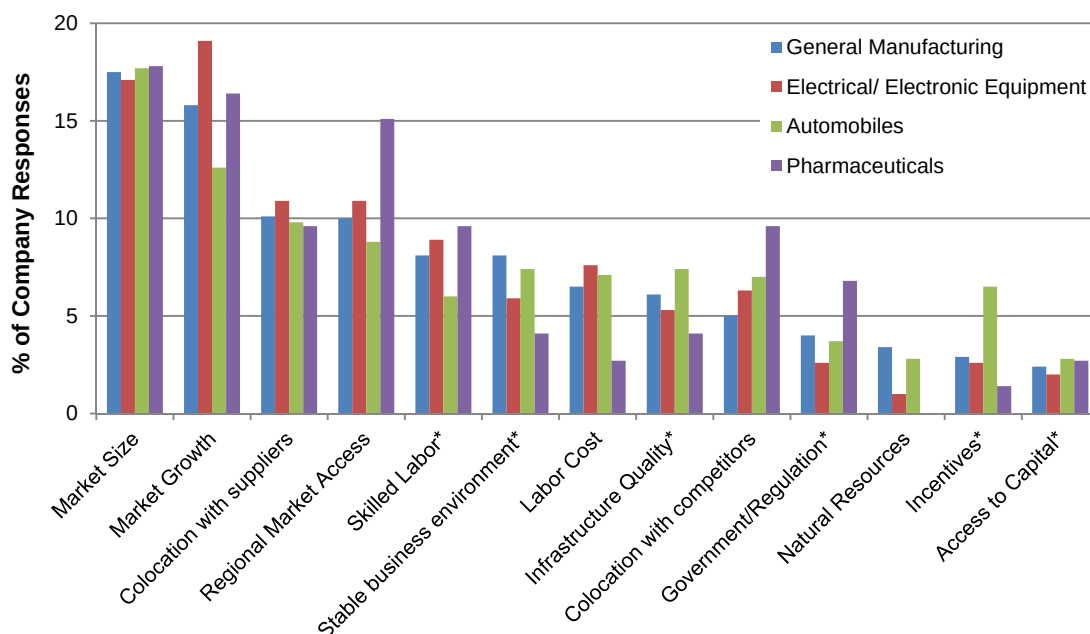
The location factors also vary in importance between different sectors. For example, the Global Competitiveness Index focuses on broad economic competitiveness, but others focus on individual sectors such as manufacturing or subsectors within manufacturing. The World Investment Prospects Survey and the Manufacturing Competitiveness Index provide data on a sample of business executives' opinions on the relative importance of different factors for individual manufacturing subsectors and manufacturing at large.

As Figure 11 indicates, the World Investment Prospects Survey revealed that the most important factors for manufacturing industries to locate within a country are market size and growth potential, co-location with suppliers, access to regional markets, access to skilled workers, and a stable business environment. As the chart shows, the lesser factors are labor costs, quality of infrastructure, co-location with competitors, regulations, access to natural resources, incentives, and access to capital (UNCTAD 2009). Data from Manufacturing Competitiveness Index, shown in Table 3, indicate the importance of similar factors in terms of average rankings on a scale from 1 to 10.

Table 2. Location factors from three reports on economic competitiveness for manufacturing.

Category	UNCTAD World Investment Prospects Survey (UNCTAD 2009)	Deloitte Manufacturing Competitiveness Index (Deloitte Council on Competitiveness 2010)	World Economic Forum Global Competitiveness Index (WEF 2011)
Factor Group/Sample Size	241	400	13,400
Market Size and Growth	Size of local market Market growth	—	Market size Macroeconomic environment
Agglomeration/Co-location	Co-location with competitors Supply chain	Supplier network Local business dynamics	Business sophistication
Regional Market/Trade	Regional market access	—	Goods market efficiency
Labor Force Issues	Availability of skilled labor	Talent-driven innovation	Higher education and training
Business Environment and Governance	Stable and business friendly environment Government effectiveness	Legal and regulatory system Quality and availability of health care Economic, trade, financial, and tax systems	Goods market efficiency Health and primary education Institutions
Access to Capital and Direct Incentives	Incentives Access to capital	—	Financial market development
Labor Costs	Cost of labor	Cost of labor and materials	Labor market efficiency
Natural Resources	Access to natural resources	Cost of labor and materials Energy cost and policies	—
Infrastructure Quality	Quality of infrastructure	Quality of physical infrastructure	Infrastructure
Support for Research and Innovation	—	Government investments in manufacturing/innovation	Innovation Technological readiness

Note: Sources are given in the first row, and the first column shows the consolidated list used in this report.



Source: Data from World Investment Prospects Survey UNCTAD (2011; UNCTAD 2009) and cited in OECD (2009). (Market size and growth are the most important location factors for all manufacturing sectors.)

Note: Bars show percentage of respondents that mentioned a specific factor as being important. An asterisk denotes a factor that is relatively movable through public policy, as opposed to broader market factors.

Figure 11. Importance of different location factors for location decisions from the perspective of different manufacturing sector companies.

Table 3. Importance of location factors for location decisions from the perspective of all manufacturing companies.

Driver	Score, 1–10
Talent-driven innovation*	9.22
Cost of labor and materials	7.67
Energy costs	7.31
Economic, trade, financial, and tax systems*	7.26
Infrastructure quality*	7.15
Investment in manufacturing and innovation*	6.62
Legal and regulatory system*	6.48
Supplier network	5.91
Local business dynamics	4.01
Health care*	1.81

Source: Data from Deloitte Manufacturing Competitiveness Index (Deloitte Council on Competitiveness 2010).

* Factor is relatively movable through public policy, as opposed to broader market factors.

Several important trends can be noted from this survey data. The first is that responses vary between surveys, perhaps depending on how the question is structured and how the samples are chosen and weighted.¹¹ For instance, data from World Investment Prospects Survey indicate that labor costs are less important than market size and growth. Deloitte's Manufacturing Competitiveness Index data do not include some of these broader factors, however. Instead, the cost of labor and materials are considered together as the second most important factor. Both surveys found policy-related factors such as infrastructure quality, business environment and governance, and legal/regulatory systems to be important factors, although less so than factors with a direct relation to costs such as labor costs, market size, and co-location effects. The World Investment Prospects Survey rates the cost of labor as less important than access to skilled labor.

Note also the relative difference between the manufacturing sector in general (shown in blue in Figure 11) and the subsectors in the high-technology areas in the WIPS data. For instance, the responses from the pharmaceutical sector (purple in Figure 11) show that labor costs are less important and access to skilled labor and co-location with competitors is more important.

Besides surveys such as these, empirical studies have not yielded generally applicable results that illuminate the location decisions of high-technology industries or advanced manufacturing as a group, although single-industry studies are more common (OECD 2011a). An OECD econometric study in 2009 found that high- and medium-technology manufacturing industries and their associated service industries were correlated with market size, agglomeration or co-location effects, labor specialization effects, and to a lesser extent, government ease of doing business. Individual advanced manufacturing industries have been studied in more detail in pharmaceuticals, for example, where scientific infrastructure and human capital have been found to be important by several studies (OECD 2010b).

The following subsections explore in more detail each of the location factors expected to be important for advanced manufacturing. We split the factors into two groups: (1) location factors that encompass broad market considerations that are difficult to influence through government policies and (2) location factors that are affected by policy choices. As we will see, competitiveness policies tend to focus on this second category of factors.

¹¹ The Deloitte survey respondents broke down as follows: Asia, 40%; U.S./Canada, 28%; Europe, 20%; and Other, 12%. The UNCTAD WIPS data, in comparison, had Asia at 30%; U.S./Canada, 34%; Europe, 30%; and Other, 6%. Thus, the MCI data more heavily captures Asia, while WIPS is more heavily weighted toward Europe. In addition, Deloitte weights data based on company size and international experience (Deloitte Council on Competitiveness 2010).

2. Broad Market Considerations

a. Market Size and Growth

Market size and overall economic growth help determine a country's competitiveness in advanced manufacturing. For example, China's large population and Brazil's population growth have been strategic assets in attracting manufacturing investment (WEF 2011). Locating production close to many or large potential customers decreases logistics costs and can avoid import tariffs, if applicable (EOP 2009). However, short of public purchase agreements or subsidies that create a local market or increase the local market size, public policies have relatively little effect over these important factors.

b. Agglomeration Effects

In general, firms prefer to be co-located in similar countries or areas with other competing firms due to the presence of supply networks, specialized services support, and the like. In addition, firms hope that knowledge spillovers will occur between supplier and service networks supporting other firms, when workers switch jobs, or in collaboration with universities or research centers (Pisano and Shih 2009). Several studies based on investment data have shown that a large presence in a single sector can induce others to relocate to that country (OECD 2011a; Crozet, Mayer, and Mucchielli 2004; Feldman 1999). For this reason, cluster development strategies tend to be a popular policy for attracting manufacturing enterprises (Popkin and Kobe 2010; National Defense University 2009). However, agglomeration in certain sectors can become a detractor for investment if an innovative firm fears losing competitive advantage through technological spillovers to other firms (OECD 2011a).

c. Regional Market Access

As previously mentioned, the size of the domestic market is a critical location factor for almost any manufacturing enterprise, although firms may choose to locate in one country for the purpose of achieving access to markets in others (Amiti 2011). Such decisions are often swayed by regional trading blocs such as the North American Free-Trade Agreement or the Association of Southeast Asian Nations Free Trade Area. By locating in one of the countries that is party to such regional agreements, the firm gains access not just to that country but to all members of the free-trade area (Athukorala and Menon 1997).

d. Labor Costs

The cost of labor can be a major driver in manufacturing competitiveness, although its importance depends directly on the labor intensity of the sector in question. Many high-technology industries are not particularly labor-intensive in the production phase

due to high levels of automation and lean-production practices, an example of the trade-off between capital intensity and labor intensity (Manufacturing Institute 2009). Such firms depend on labor for design and innovation purposes, because advanced manufacturing companies tend to be R&D-intensive.

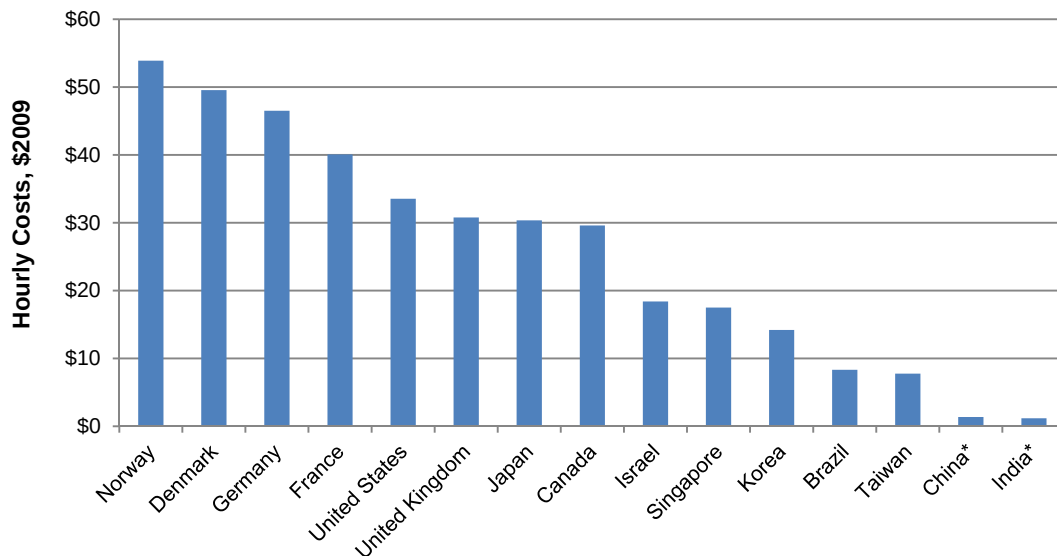
Consumer electronics is an example of how the location of research and production reflects comparative advantages. Labor-intensive assembly is typically located in areas with low labor costs and design, and research is located in areas with highly skilled labor (Pisano and Shih 2009). However, because of the advantages to co-locating design and manufacturing (see Section 4.B.3.d), low labor costs that drive assembly and production can eventually attract higher value-added portions of the supply chain like complete product assembly and design (Pisano and Shih 2009).

These survey statistics show that labor cost can have medium to high importance for different manufacturing sectors. Data on foreign direct investment in manufacturing reinforces the idea that labor costs are not one of the most important location factors—the United States and other high-wage countries remain leaders in attracting foreign investment (Manufacturing Institute 2009). Even among these higher wage countries, manufacturing hourly compensation costs in the United States in 2009 were lower than in 12 European countries and Australia, but higher than those in 20 other countries.

As Figure 12 shows, the United States pays \$33.53 (U.S. dollars, 2009) in average compensation, compared with Japan at \$30.36 and Germany at \$46.52 (BLS 2011b). However, all three countries remain in the top 10 of major indices of competitiveness such as the Global Competitiveness Index (United States ranks 5, Germany ranks 6, and Japan ranks 9) (WEF 2011).

a. Natural Resource Endowments or Prices

For certain industries, the local availability or price of certain natural resources can be an important location factor. For instance, energy-intensive industries such as basic metals, cement, and glass tend to locate in areas of low energy prices (Michielsen and Gerlagh 2011). Similarly, China has developed a lead in several sectors dependent on rare-earth elements due to its near monopoly in this sector. While policies such as environmental regulation or trade policy can affect the availability or price of natural resources, countries are to some extent limited in their options to change this location factor.



* Comparable 2009 data for China and India are not available as statistics on employment and wages do not follow international standards. Data shown are estimates from 2008 for China and 2007 for India.

**Figure 12. Manufacturing hourly compensation (BLS 2011a)
including all direct costs to firms.**

3. Location Factors Affected by National Policies

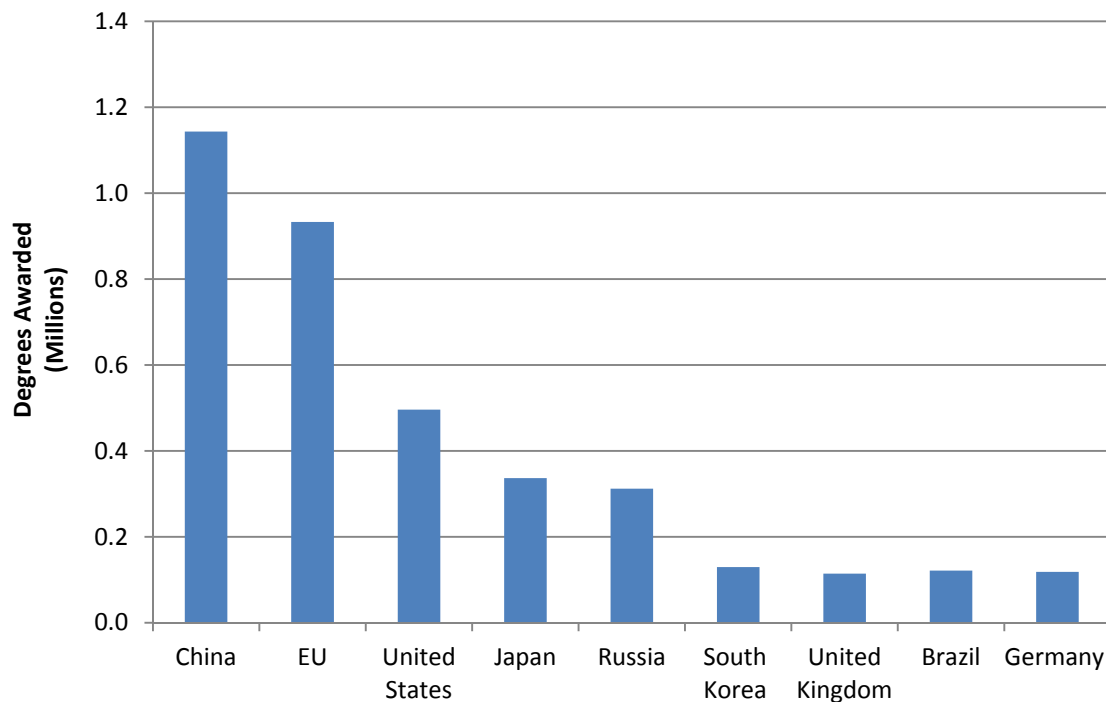
a. Labor Force Issues: Education and Skill Development

Education and workforce skills are critical elements to the development of advanced manufacturing. In fact, the Manufacturing Competitiveness Index survey found that access to high-quality labor, including scientists and engineers, is the top-ranked factor for manufacturing competitiveness (Deloitte Council on Competitiveness 2010). While there is debate on the precise definition and role of skills in innovation—and on which skills are required in the manufacturing sector—it is generally accepted that countries with high academic standards not only have increased participation in post-secondary education and training, but they create a workforce that has the potential for engaging in innovation within fields such as advanced manufacturing (Toner 2011). With respect to the United States, some experts interviewed were concerned about the quality of STEM education and the resulting consequences for manufacturing innovation (Suri 2011; Chen 2011b; Weitzman 2011). At the university level, a few experts recommended that the United States offer engineering degrees in manufacturing that train workers to understand the entire process, not just one facet of the manufacturing process (Suri 2011; Chen 2011b).

The pursuit of education is rising across developed and developing countries. From 1998 to 2009, the proportion of the population of OECD countries that had not

completed secondary education dropped from 37% to 29% (OECD 2011c). Changes in production technology and the organization of work are claimed to demand higher skill levels that in part have led to a continued rise in educational levels (Toner 2011). For those countries at the forefront of advanced manufacturing, technical training is considered extremely important.

One example of the effect of varying national educational systems is in the output of bachelor's-level scientists and engineers, which may be considered a proxy of a country's future workforce capabilities in innovation.¹² As of 2008, China had the largest number of science and engineering undergraduates, followed by the European Union (EU-27), the United States, and Japan (see Figure 13). The quality of some of China's bachelor's-level scientists and engineers has been questioned, yet it is generally agreed that the sheer size of the country's science and engineering workforce is advantageous (Wadhwa 2008). Over the next 20 years it is expected that more advanced skills will be needed for workers in manufacturing and other sectors, compared with the skill needs of the past (Autor 2010).



Source: National Science Board (NSB 2012, Appendix Table 2-32).

Figure 13. Number of undergraduate degrees awarded in science and engineering fields, 2008 or most recent year.

¹² Researchers in R&D are professionals engaged in conceiving or creating new knowledge, products, processes, methods, or systems and in managing the resulting projects.

About 1 million science and engineering Ph.Ds. have been granted annually in China in recent years. Despite these large numbers, comparing skill competencies with other countries is difficult due to the changing nature of national education systems over time (Toner 2011). Nonetheless, the impact of a highly educated workforce on such a large scale will help spur economic growth (Chen 2011b; Suri 2011; Weitzman 2011).

In the United States, experts stressed the need for an education culture that not only better educates, but also inspires students to take up careers in science and engineering, fields currently perceived as too difficult or uninviting. Recent reports on this topic by the President's Council of Advisors in Science and Technology (PCAST) (PCAST 2010a, 2010b) have called for STEM curriculum that requires students to get a firm grounding in the principles of computing, going well beyond simply being able to use computational systems, to understanding the role of computing in solving problems in different disciplines.

Beyond educational attainment, workforce skill-formation systems are varied across developed countries, especially when considering the role of vocational skills. This gives rise to large variations in the performance of vocationally trained workers in countries. For example, workers in the United Kingdom are less able to deal with technological change and more complex problem-solving due to their lack of skills (Brockmann, Clarke, and Winch 2008). In Germany, 60% of high school students divide their time between school and learning a trade (Economist 2011b). Germany and Switzerland also have apprenticeships that are integral to the secondary education system. Many institutions also require completion of an apprenticeship before entering an advanced degree program (NRC 2003a).

The United States has apprenticeship programs for workers at the high school and community college level, but they are not widespread. In 2007, the latest year for which data are available, there were about 465,000 apprentices in 28,000 Registered Apprenticeship programs. Although these programs were in important sectors, including construction and building trades, building maintenance, automobile mechanics, steam fitting, machinist, tool and die, they only reached a fraction of the workforce (NRC 2003a). At the university level, cooperative-education provides experiential learning to prepare students for professional careers by combining academic training with work experience. Co-op students usually work for one or two semesters and then return to school for academic study. Many universities offer cooperative-education programs to engineering students, although it is available to other majors as well.¹³

Countries use different strategies to develop and maintain their workforce. For example, Germany has a strong culture of workforce development and compensation. During the recession in 2009, German companies agreed to cut down working hours in

¹³ The American Society for Engineering Education (ASEE), <http://ceed.asee.org/>.

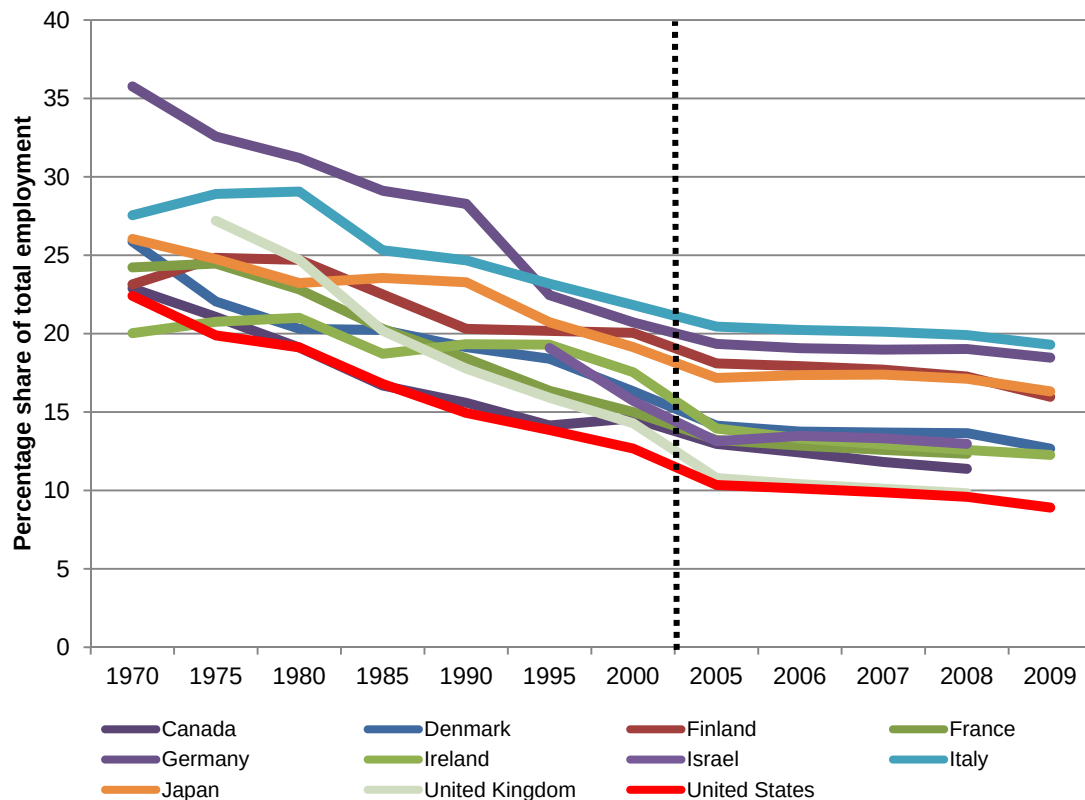
the manufacturing sector instead of laying off workers, with the government replacing the lost pay for the workers (Möller 2010). As a result, when the economy picked up, German companies were ready to ramp up with the right workforce in place.

Demographic changes expected over the next two decades are also expected to change the composition of the labor force. China's population over age 65 is predicted to double over the next 25 years; in the United States, it is predicted to take 70 years (Stone 2010). Thus, education, workforce training, increasing automation, and other factors that increase productivity will become increasingly important as job-replacement needs rise with retirements.

While demographic shifts and retirements are driving an increased need for manufacturing jobs, productivity increases continue, making it difficult to know how many manufacturing jobs will exist in the future. The percentage of manufacturing employment has steadily declined over the past four decades in OECD countries as shown in Figure 14. In absolute numbers, manufacturing employment is highest in the United States, with just under 15 million employees (10% of total employment in 2010), followed by Japan with 10 million (17%) and Germany with 8 million (21%) (BLS 2011a).

b. Business Environment and Governance

The broad categories of the stability of the business environment and the quality and efficiency of the location's governance and institutions include several different types of indicators associated with the general ease of doing business, costs associated with doing business, and ability for a firm to protect its intellectual property. As seen previously in Table 2, different organizations classify these indicators differently, including categories on business-friendly environment, goods and labor market efficiencies, legal and regulatory systems, quality of health care, and trade and tax systems. Government support for innovation and research could be included in such a category, but given innovation's particular importance to advanced manufacturing, we opted to consider them together in a separate section (4.B.3.d).

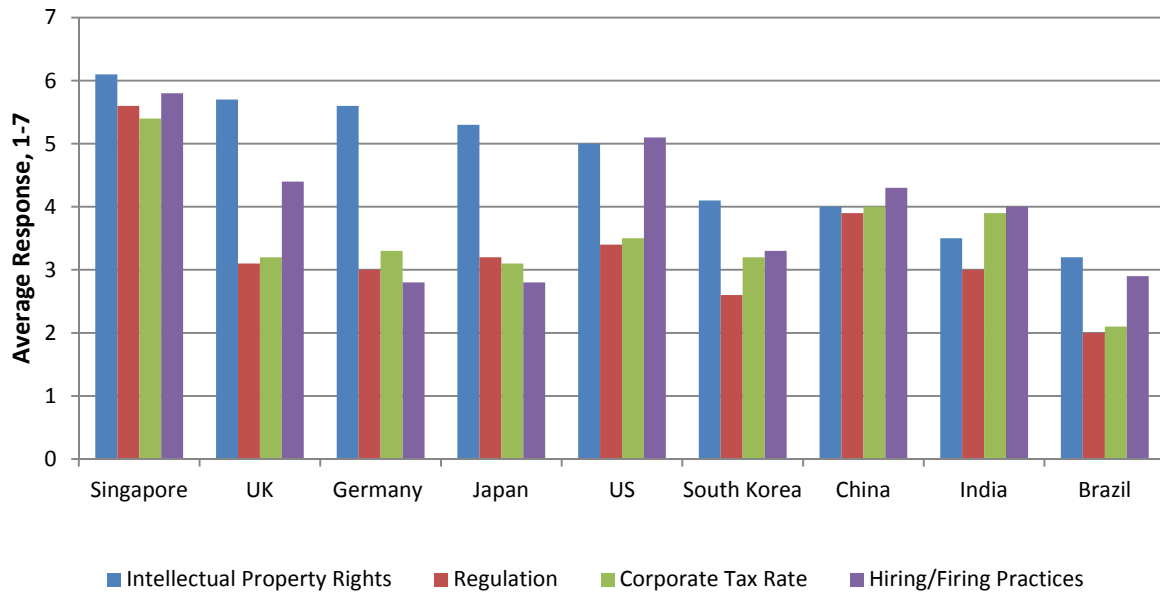


Source: OECD (2011d).

Note: The dotted line indicates a change in the abscissa. To the left, the years are in intervals of 5 and on the right they switch to an interval of 1.

Figure 14. Manufacturing shares of total employment across various OECD countries.

The Global Competitiveness Index (GCI), perhaps the most comprehensive survey of business executives on competitiveness issues, asks questions on many types of indicators that fall into this category. For instance, the GCI includes the quality of institutions as the first pillar of economic competitiveness and measures or ranks countries based on the protection of physical and intellectual property rights, judicial independence, corruption, burden of regulation, and the strength of protection for investors (WEF 2011). Similarly, the efficiency of goods and labor markets is measured by such criteria as the total corporate tax rate, effectiveness of monopoly regulation, average size of trade tariffs, hiring and firing practices, and cooperation between labor and employers (WEF 2011). All these factors are related to the barriers associated with developing and commercializing advanced manufacturing products at low overall costs. Figure 15 shows several responses from the GCI across these categories.



Notes: Data are sorted by responses to the following questions on intellectual property rights (World Bank 2011): How would you rate intellectual property protection, including anti-counterfeiting measures, in your country? [1 = very weak; 7 = very strong]; How burdensome is it for businesses in your country to comply with governmental administrative requirements (e.g., permits, regulations, reporting)? What impact does the level of taxes in your country have on incentives to work or invest? [1 = significantly limits incentives to work or invest; 7 = has no impact on incentives to work or invest; How would you characterize the hiring and firing of workers in your country? [1 = impeded by regulations; 7 = flexibly determined by employers].

Figure 15. Average ranking (1 = min, 7 = max) regarding different factors associated with ease of doing business in respondents' countries.

Some countries, including Singapore, routinely perform well in the rankings of government effectiveness and ease of doing business. Other developed nations tend to have split rankings, where the protection of intellectual property is highly valued by innovative companies, but other types of regulation, such as environmental and labor, are seen more negatively. For example, U.S. manufacturing companies report that the cost of regulatory compliance in the United States is high by global standards (Manufacturing Institute 2009).¹⁴ Large developing countries, which may have less stringent environmental and labor protection standards, can also have lower scores due to other factors related to the ease of doing business, such as the legal institutions, the ease of starting or closing a business, or the presence of corruption (World Bank 2011; WEF 2011). For instance, it takes 6 days to start a business in the United States, 38 days in China, and 120 days in Brazil (World Bank 2011).

An important aspect of governance for advanced manufacturing is the protection of intellectual-property rights. The lack of protection for intellectual-property rights in many developing countries is currently seen as a major deterrent for highly innovative sectors

¹⁴ This is based on company reporting and is likely true compared with emerging economies such as China, but not compared with Europe and Japan.

such as those involved in advanced manufacturing. Research shows that countries that having strong intellectual-property protections can help attract foreign investment, but the lack of such protections is not necessarily a deal breaker. For example, companies can choose to produce some technologies in countries with weak protections while complementary technologies are produced in countries with greater intellectual-property protections (OECD 2011a; Thursby and Thursby 2006).

c. Infrastructure Quality

The quality of public infrastructure has been found to be an important location factor, and in some cases, it can compensate for relatively higher corporate taxes (Bellak, Leibrecht, and Damijan 2009). The GCI classifies three different types of infrastructure in its rankings: transportation, energy, and telecommunications (WEF 2011). Such public infrastructure acts to lower fixed costs for a firm because it replaces investments the firm would otherwise have to privatize (Egger and Falkinger 2006). For example, in countries with lower quality electricity grids, firms can be forced to generate their own electricity using fuel generators. In addition to raising fixed costs (the cost of the generator), this practice increases energy costs because small generators are usually less efficient than larger central electricity generators. Similarly, dependable telecommunications infrastructure is vital for multinational firms with global supply chains (Bellak, Leibrecht, and Damijan 2009).

d. Government Support for Innovation

To develop advanced manufacturing, government policies may be designed to support innovation and research through strong partnerships between academia, government, and industry. Advanced manufacturing requires high and sustained levels of funding for breakthrough advances in science and technology but also in business processes. Support can be achieved through different avenues, such as direct grants for research or public-private partnerships (PPPs). PPPs are used to spur innovation in manufacturing through joint funding by government and one or more private-sector companies, academic entities, or nonprofit organizations (Federal laboratories and other research organizations). The sidebar “Examples of Public-Private Partnerships” provides four global examples.

Rationales for the government to use public money to support private innovation mainly revolve around the concepts of market failure or inadequate market incentives for innovation. In general, the private sector will underinvest in research and development for two reasons. First, the type of frontier research needed for advanced manufacturing is usually risky and thus difficult to justify to shareholders, despite the high societal rate of return through wealth and job generation. Second is the lack of “appropriability,” the economic concept of a firm being able to capture the advances that come from innovative

research without losing their competitive advantage due to knowledge spillovers, similar to the arguments for co-location previously discussed (PCAST 2011).

Examples of Public-Private Partnerships

The Department of Energy's *Energy Innovation Hubs* are multi-institutional, multi-investigator research centers that bring together top researchers from all sectors with the goal of overcoming technological barriers to transformative advances in energy technology. The Hubs are modeled after management approaches used by the Manhattan Project, which developed the atomic bomb, and Bell Labs, which invented the transistor in the 1950s. Each Hub's management structure will allow scientist-managers to execute quick decisions to shape the course of research, and links to industry will bridge the gap between basic scientific breakthroughs and industrial commercialization. The Hubs are different from other DOE R&D programs because of their larger scale and their sole focus of finding energy-technology solutions in important areas such as battery and energy storage.

Source: <http://energy.gov/articles/what-are-energy-innovation-hubs>.

The *Factories of the Future* is one of three public-private partnerships with the goal to create an industry-led research and innovation initiative aimed at launching hundreds of market-oriented cross-border projects throughout the European Union. These projects will produce prototypes and models to be applied in a wide range of manufacturing sectors. The four research priorities, selected after consultation with hundreds of stakeholders, are sustainable manufacturing, high-productivity manufacturing, ICT-enabled intelligent manufacturing, and materials in manufacturing. This public-private partnership program is unique because of its focus on the manufacturing enterprises of the EU, in particular small and medium enterprises.

Source: <http://www.effa.eu/>; http://ec.europa.eu/research/industrial_technologies/factories-of-the-future_en.html.

The German *Fraunhofer Institutes* is Europe's largest research consortium, consisting of a collection of public and private organizations that focus on manufacturing and related topics and conduct applied research to benefit industry. Using a decentralized model of strategic planning done at the institute level and coordinated within the Fraunhofer research groups, they develop complex system solutions to solve industry challenges. The Fraunhofer Institutes are continually adapting their profiles to meet current demand, to respond to the present and predicted needs of the market. They also influence the development of emerging manufacturing technologies through their own preliminary research.

Source: <http://www.fraunhofer.de/en/about-fraunhofer.html>.

The Chinese government has established several national engineering research centers, each of which focuses on a topic of national interest and employs the use of the state, academic, and industry partnerships and resources. One example is the *National Engineering Research Center for Industrial Automation*, sponsored by the State Planning Commission and founded at Zhejiang University. The research areas this center focuses on include modeling, advance control and process optimization, production scheduling and management decision-making, redundant control and fault detection, and integration of generalized industrial process-automation systems based on network and databases for industrial processes. The center focuses on the standardization and commercialization of major research outcomes to advance the overall level of the industrial process automation in China.

Source: http://www.cse.zju.edu.cn/english/redir.php?catalog_id=30975.

A few of the interviewed experts noted that other countries rely on the United States to develop technologies that they then adopt to produce their own goods and services (Herr 2011; Rocco 2011). Many other small, amorphous mechanisms of knowledge transfer by which intellectual property developed in the United States are informing development in other countries. For example, India follows the policy of frugal

innovation whereby innovators adapt more expensive technology to lower cost solutions that can be marketed to large numbers of people with lower incomes (Engineering and Physical Sciences Research Council 2008).

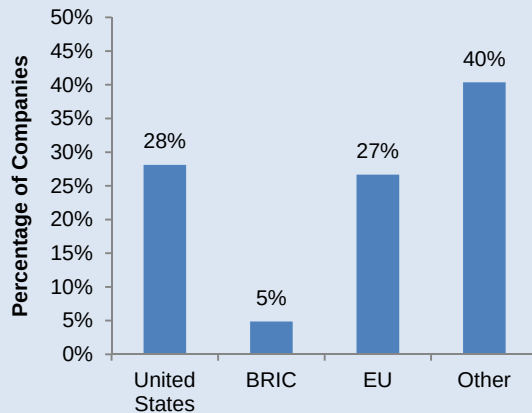
e. Access to Capital and Direct Incentives

Given the increased competition for advanced manufacturing, many countries are now creating policies specifically designed to attract investment, including R&D tax credits to encourage innovation, low-interest loans and grants, and subsidized services/preferential treatment in regulation. Access to capital is a necessary first ingredient in nurturing entrepreneurs and innovators. Countries also use investment promotion and direct advertising or recruiting of foreign multinationals. The WIPS data show that many companies do not openly admit to being swayed by such incentives, and existing studies have mostly been unable to determine the effect of such incentives due to the difficulty of retrospective analysis (Criscuolo 2009). While it is unlikely that such direct incentives will lure a firm to a country with weak overall location factors, such incentives could be the deciding factor between several locations with similar scores in other areas, particularly if the locations are in the same region (OECD 2011a).

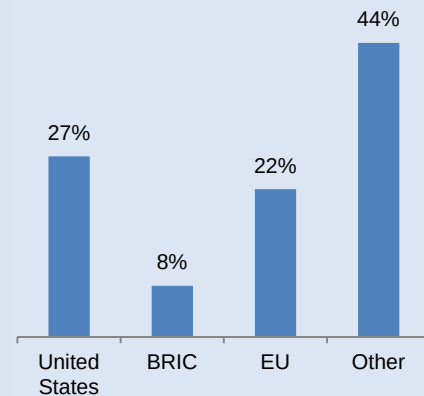
Distribution of Publicly Held Manufacturing Companies by Country/Region

Each year, *IndustryWeek* identifies the top 1,000 publicly held manufacturing companies based on their revenue. Although not a complete set of firms companies, as privately held companies are not included, this measure of top 1000 firms provides one indicator of relative manufacturing strength by country or groups of countries. Companies are assigned to a country based on where their headquarters are located. Petroleum products and coal are excluded from the analyses, since these products are not manufactured. Before they were excluded from the analysis, petroleum companies accounted for 27% of the revenues and 116 of the companies. Excluding petroleum companies, over one-fourth (28%) of these top manufacturing companies (based on revenue) are U.S. companies; 5% are BRIC (Brazil, Russia, India, and China) companies, and 27% are European Union (EU-27) companies. The balance, 40%, is quite large but is distributed over Australia, Indonesia, Malaysia, New Zealand, Philippines, Singapore, Bermuda, Canada, Cayman Islands, Chile, Mexico, Hong Kong, Japan, South Korea, Taiwan, Thailand, Turkey, Israel, Saudi Arabia, Norway, Switzerland, and South Africa. The distribution is similar when viewed by number of companies (see charts on the next page).

Percentage of Companies by Region by Revenues

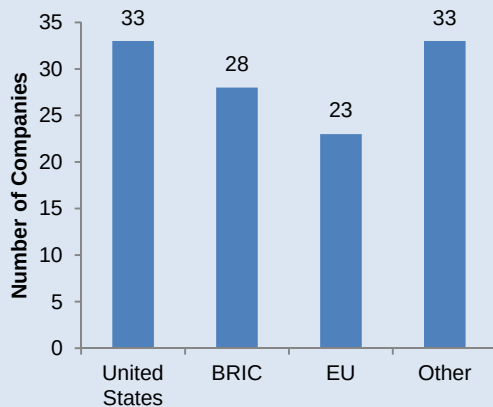


Percentage of Companies by Region by Number of Companies



Source: IndustryWeek 1000, report based on the 1,000 largest publicly held manufacturing companies based on revenue, excluding petroleum companies (which brings the count to 884 firms), <http://www.industryweek.com/research/iw1000/2011/iw1000rank.asp>.

Number of Companies with Growth Rates above 30%



Source: IndustryWeek 1000, excluding petroleum companies (which brings count to 884 firms), <http://www.industryweek.com/research/iw1000/2011/iw1000rank.asp>.

What is interesting about these data is not that the largest companies are in the United States or Europe, but that the distribution of highest growth firms (those firms with growth rates above 30%) is different than the distribution based on revenues. For example, while 33 of the 117 high-growth-rate firms have their headquarters in the United States (28%), 28 are from BRIC countries (24%), 23 are from the EU (20%), and 33 are from elsewhere (28%). So, although companies in BRIC countries do not have an overall presence, they have a similar number of companies with a high growth rate as the US, EU, and Other countries.

Within sectors, the United States accounts for more than 50% of the revenues across these companies in aerospace and defense, furniture and fixtures, electrical equipment and appliances, and medical instruments and equipment.

The European Union is strongest in communication equipment (60%), apparel (55%), stone, clay, glass and concrete products (52%) but they are also quite strong in areas similar to the United States such as aerospace and defense, plastics, machinery, beverages, and chemicals. The BRIC countries do not dominate in any sector, but do have a presence in textiles (44%), fabricated metal parts (24%), and primary metals (18%).

C. National Policies and Investments

In this section, we examine overall manufacturing and innovation strategies of six leading manufacturing countries to identify what may lead to success in attracting and maintaining an advanced manufacturing base. The countries were chosen because of their emerging capabilities (Brazil and China) or their current and potential capacity for advances in manufacturing (Germany, Japan, Korea, and the United Kingdom). Appendix E provides details of the policy environment of the six countries related to competitiveness in innovation and manufacturing. We did not look at Russia because of the limited amount of information available, but we did prepare a brief summary of manufacturing in Russia—see the sidebar “Manufacturing in Russia” at the end of this chapter.

1. Brazil

Brazil’s priority is to continue to develop its manufacturing sector, with a focus on the defense industry. Brazil partners with other countries in return for access to raw materials and natural resources. Although Brazil’s investment in R&D is low, investment increased to 1.5% of GDP in 2010, and Brazil is requiring industry to invest in research through several programs that encourage development geographically across states. Brazil uses government procurement to ensure purchases of new products. It has initiated new programs to encourage students to obtain advanced degrees, to study overseas, and to work for industry when they graduate.

2. China

China is developing a strong advanced manufacturing sector through multiple innovation strategies, primarily technology adoption tailored to meet its internal needs (often referred to as indigenous innovation, *zizhu chuangxin*), and development of dual-use technologies that meet both military and domestic needs. (See sidebar “*Zizhu Chuangxin* (Indigenous Innovation).” in Chapter 3, Section B.4.)

China’s twelfth 5-year plan identified seven strategic emerging industries to grow over the next 5 years (from 5% of GDP to 8%). Three out of the seven industries focus on energy (clean-energy technology, alternative energy, and clean-energy vehicles). The other industries focus on information technology, biotechnology, high-end equipment, and new materials (Economist Corporate Network 2011; Casey and Koleski 2011). (See sidebar “Strategic Emerging Industries in China” on the next page”)

The seven industries have strong links to manufacturing. China has a large, relatively low-cost, but increasingly educated workforce and large government investment in manufacturing and innovation strategies. However, China faces many

challenges to its fast-paced growth, including managing a rapidly aging population, increasing inequality, and air and water pollution.

Strategic Emerging Industries in China

In October 2010, China announced an initiative to broaden the government's focus on promoting the development of technologically heavy enterprises. The State Council's *Decision to Accelerate the Development of Strategic Emerging Industries* calls for extending support for industries in seven emerging sectors where “revolutionary breakthroughs” are possible (Guofa 2010). China's twelfth 5-year plan (in the part titled “Transforming growth pattern, create a new scenario for scientific development”) provided further clarification on the focus for each strategic emerging industry (Springut, Schlaikjer, and Chen 2011; Ang, Heidel, and Wong 2012):

- **Energy conservation and environmental protection industry.** Develop key technological equipment for efficient energy conservation, advanced environmental protection and resource recycling, products and services.
- **New-generation IT industry.** Develop new-generation mobile communication, new-generation Internet, three-network convergence, Internet of things, cloud computing, integrated circuits, new displays, high-end software, high-end servers and information services.
- **Biological industry.** Develop biopharmaceuticals, biomedical engineering products, bio-agriculture and bio-manufacturing.
- **High-end equipment manufacturing industry.** Develop aviation equipment, satellites and applications, rail-traffic equipment, and intelligent manufacturing equipment.
- **New energy industry.** Develop new-generation nuclear energy and solar energy, photovoltaic and photo-thermal power generation, and wind-power technological equipment, intelligent power grids, and biomass energy.
- **New material industry.** Develop new functional materials, advanced structural materials, high-performance fibers and compound materials, and common basic materials.
- **New energy automobile industry.** Develop plug-in hybrid-electric vehicles, pure electric vehicles, and fuel-cell automobile technologies.

The strategic emerging industries overlap heavily with 16 “megaprojects” developed as part of the Medium and Long Range Plan (MLP) for S&T, at a cost of 600 b RMB (Naughten and Ling 2011). Unlike megaprojects, however, they are more focused on developing cutting-edge technologies—rather than infrastructure development, the focus of the megaprojects.

The 5-year plan sets a goal of 8% for the proportion of the added value from the new strategic industries to GDP (Ang, Heidel, and Wong 2012). The government will not simply inject isolated government capital in the strategic emerging industries but pursue related policies. For example, the Strategic Emerging Industries Decision calls specifically for:

- Increasing R&D expenditures in enterprises, industrial pilot/demonstration projects, and research alliances involving labs and universities led by backbone industries.
- Creating financial incentives for intellectual property development.
- Improving research environments.
- Implementing and supporting major engineering projects.
- Building improved financial and consulting support for industry.
- Building mechanisms to aid the commercialization of technology.

3. Germany

Germany uses market-pull strategies to support innovation. These strategies aid start-up companies, have an increasing emphasis on public procurement of new technologies, and use standards to drive innovation (Bleviss 2010). Germany also supports an emerging defense and national security industrial policy through the development of high-technology products. Germany's Mittelstand philosophy is similar to what *The Economist* calls China's "Bamboo Capitalism," or growth in entrepreneurship (Economist 2011a). This Mittelstand philosophy is noted for its attention to detail, financial caution, and cooperation between supervisor and employees (Economist 2011b). Similar to China, Germany is targeting policies to facilitate entrepreneurship and access to capital, as well as specific sectors (security, health, transportation, and climate.) Although Germany's workforce is well educated, a relatively low number of its workers have advanced degrees. New policies with the goal to increase the number of Ph.Ds. in the workforce have stopped the downward trend in university entrants. To maintain their manufacturing skills and employment during the recent downturn, they reduced working hours and emphasized cross training (Möller 2010).

4. Japan

Japan uses push-funding strategies and targets sectors that are critical to its economy, such as security and access to materials. Of the six countries examined, Japan spends the largest percentage of its GDP on R&D. It has strong manufacturing sectors (vehicle, information technology, electronics, robots, and satellites), and industry partnerships are more prevalent than academic ones. To encourage entrepreneurship, Japan has strengthened intellectual-property rights, decreased royalty costs, and started programs to increase industry-academic partnerships. Japan is developing alternative technologies that do not rely on rare earths and has become extremely efficient in use of energy. It is also developing policies to increase foreign direct investment, which is quite low compared with that in other countries. Japan faces workforce challenges due the decline of the educated, but aging, population and restrictive immigration policies.

5. Korea

Korea's innovation philosophy is focused on developing its manufacturing sector. Korea is a leader in shipbuilding, semiconductors, and displays, and its Vision 2025 plan has made defense research a priority. Like Japan, Korea has a high rate of spending (as a percentage of GDP) on R&D. It recently signed an agreement with India to develop and co-produce dual-use products in marine systems, electronic

and intelligent systems, and other state-of-the-art technologies (*India South Korea Defense Cooperation* 2010). Korea does not have strong industry and academic linkages, as the private sector conducts most of its own research, resulting in low rates of entrepreneurship and venture capital. Korea has implemented policies to counter the low rates of foreign direct investment, including improving access to capital markets and providing investment incentives. The Korean workforce is rapidly aging due to low fertility rates.

6. United Kingdom

The United Kingdom has a strong manufacturing industry with a focus on developing pharmaceuticals, health, and defense-related research. It uses demand or pull strategies for innovation through government procurement and standards. Priority areas for defense-related research include data and information fusion, human factors integration, electromagnetic remote sensing, and systems engineering for autonomous systems. The United Kingdom has recently developed several new innovation policies to create stronger links between academia and industry; to designate a portion of government funding to small and medium companies in the defense, health, and construction sectors; and to improve productivity by maintaining and improving standards in biometrics, nanotechnology, and regenerative medicine. The UK workforce is educated but with a low proportion of R&D personnel compared with other European Union countries. Students are less likely to study engineering and science, and only half of those who do pursue science-related careers.

Manufacturing in Russia

On paper, Russia's innovation system includes all the elements of a functioning national innovation system: sizable business R&D activities, a substantial public research sector, infrastructure and institutions to support commercialization of public research, and government programs to promote private and public R&D and innovation in priority areas or more generically.

In reality, however, Russia continues to suffer from issues surrounding a low rate of investment, disincentives in the business environment (notably the lack of competition), inefficiencies in state-owned enterprises, poorly designed and enforced innovation-related institutions (e.g., knowledge networks, intellectual-property rights), unbalanced international linkages, and governance systems' encouragement of partly competing visions, as well as overlapping and too top-down policy implementation (OECD 2011d). According to OECD, however, the biggest challenge faced by the Russian innovation system is the lack of centrality of firms.

Features of the Russian Manufacturing Sectors

Manufacturing in Russia is dominated by low-value-added goods and natural-resources-intensive products, in particular oil and gas products. However, the economic dominance of the natural resources sector has been changing, and in 2010, manufacturing provided 60% of aggregate GDP growth in Russia (Ernst & Young 2011). Advanced manufacturing, however, remains a smaller fraction of total manufacturing. According to the World Economic Forum calculations, in 2007, manufacturing of high-tech products took up only 0.7% of GDP—less than one-seventh that in China and half that in Brazil (WEF 2011b).

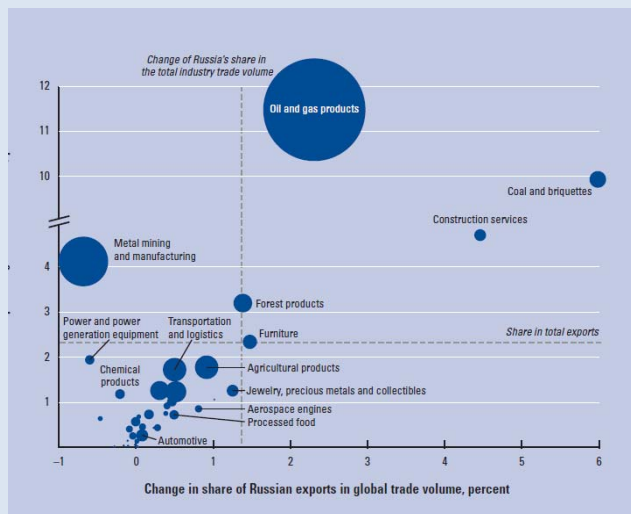
As with production, Russia's exports are dominated by oil- and gas-related products, with about two-thirds of exports coming from the petroleum sector. Areas where Russia has gained ground (as compared with other countries between 1997 and 2007) are equally low-value-added goods and services, such as coal and briquettes, construction services, forest products, and furniture. The figure at right showcases Russia's main manufacturing exports and changes in them since 1997.

Experts believe that the nation's decline in its manufacturing competitiveness is a result of the combination of an increase in real wages and shortcomings of the business climate (Desai 2008). But as observed earlier by OECD, the main obstacle lies with firms themselves, which are seen as having too few capabilities to innovate, little absorptive capacity for external innovations, and weak links to research institutes and universities, and with a general political environment that provides few incentives to innovate (WEF 2011b).

Future Plans

In recent years, Russia has attracted foreign direct investment in some manufacturing sectors. Indeed, over half the total foreign direct investment in Russia in 2010 was used to create projects in the Russian manufacturing sector (most notably automotive). This can be explained in part by a government policy to facilitate automotive production (Ernst & Young 2011).

The Ministry of Economic Development has also approved plans to significantly increase its support for innovative activities. In the recently approved Innovative Russia 2020 blueprint, the government proposes to raise science funding to at least 2.5% of GDP by 2020. The strategy foresees an increase in the share of innovatively active companies from current levels of 9.3% to 40%–50% by 2020, as well as growth in Russia's share of the global high-technologies market. The total funding for innovation for the next 10 years is estimated at over \$500 billion, which includes expenses of creating effective incentives for increasing the flow of qualified specialists, active entrepreneurs, and creative youth into innovation-based economic sectors (European Commission 2011).



Russia's Exports (2007) and Changes Since 1997

5. Future Scenarios and Concluding Comments

A. Future Scenarios

Our research into advanced manufacturing points to an increasingly automated world that will continue to rely less on labor-intensive mechanical processes and more on sophisticated information-technology-intensive processes. This trend will likely accelerate as advances in manufacturing are implemented. In this chapter, we propose advanced manufacturing scenarios 10 and 20 years out. These scenarios are formulated based on our research in the previous chapters.

1. Next 10 years

Manufacturing will become increasingly globally linked as automation and digital supply-chain management become the norm across enterprise systems. This will be possible through the adoption of adaptive sensor networks to create intelligent feedback that will inform decision-making and analyses in real-time. The migration to cloud sharing will be the “computing commons” for small and medium manufacturing enterprises. There will be a need for secure management of massive amounts of data generated within the supply chain and manufacturing facility, with an accompanying need for cyber-security of globally linked enterprise systems. The use of modeling and simulation will accelerate the development of new materials, products, and processes in diverse fields such as integrated computational materials engineering (ICME), nanoelectronics, and synthetic biology.

Countries and companies that invest in cyber and related physical infrastructure will be positioned to lead by exploiting the resulting increased flow of information. The underlying expansion in computing and sensing capabilities will, in turn, enhance the importance of semiconductors beyond today’s computing and information technology sectors. Intelligent sensor networks will allow the creation of increasingly autonomous systems across sectors, such as transportation, energy management, and health. The use of large datasets (referred to as “Big Data” in scientific and business applications), will rely on increasingly sophisticated approaches to visualization and analytical tools to detect patterns, accelerate discovery, and reduce risk.

Advanced manufacturing processes will likely be more energy and resource efficient, as companies strive to integrate sustainable manufacturing techniques into their

business practices to reduce costs, to decrease supply-chain risks, and to enhance product appeal to some customers.

Increasing demand for flexibility and customization may lead to the proliferation of additive manufacturing for customized geometry and integrated computational materials engineering for customized materials. These trends will allow for local manufacturing that adapts to the needs of the region as well as the flexibility to produce for a global market. Manufacturers will differentiate themselves by how well they make use of data and how creative they are in designing and marketing new products. New tools will facilitate the analysis of massive data sets to detect patterns, accelerate discovery, and reduce risk.

From a technological standpoint, advances in materials and systems design will likely accelerate and transform manufactured products. For example, large global investments in graphene and carbon nanotubes for nanoscale applications have the potential to change electronics and renewable energy applications. Further, self-assembly-based fabrication processes and biologically inspired designs will be integrated into the manufacturing process as technologies advance and cost-effective implementations are realized.

Biologically inspired designs, nanoscale and self-assembly based fabrication processes will be integrated into the manufacturing process as technology advances. Bio-mimetics, or biologically-inspired design and materials will yield unique properties and functionality and cut across technology areas, such as bio-electronics. Synthetic biology has the potential to engineer and use biology for manufacturing applications. These developments will form the basis for new ideas and approaches in all domains and have the potential to revolutionize industries.

Establishing an advanced manufacturing sector will continue to be a priority for many countries, with progress depending importantly on market factors. Companies will locate in countries that have large and growing markets. Country-specific policies that spur advanced manufacturing will set the stage for manufacturing sectors to emerge in both developed and developing countries.

2. Next 20 years

In 20 years, many of the early trends and techniques that begin to emerge at 10 years are expected to be more fully adopted, with advanced manufacturing pushed toward new frontiers.

Manufacturing innovations will displace many of today's traditional manufacturing processes, replacing labor-intensive manufacturing processes with automated processes that rely on sensors, robots, and condition-based systems to reduce the need for human interventions, while providing data and information for process oversight and improvement.

Advanced manufacturing will increasingly rely on new processes that enable flexibility such as biologically inspired nanoscale fabrication processes and faster additive manufacturing techniques capable of building at area or volume rather than by layering materials.

Manufacturers will increasingly use advanced and custom-designed materials developed using improved computational methods and accelerated experimental techniques. Advances in design of materials will rely on a combination of computational methods and accelerated experimental techniques to decrease the time from concept to production. The coordination of materials designs, processing, and product engineering will become more efficient as computational abilities continue to improve.

Integrated computational materials engineering and additive manufacturing processes will begin to replace traditional processes. This will have the added benefit of integrating sustainable manufacturing processes by reducing use of resources and eliminating waste across the manufacturing enterprise. Additive manufacturing will allow for increasing manufacture of customized products. In 30 years, advanced manufacturing is expected to be heading toward atomic-level precision-manufacturing processes.

Synthetic biology could change the manufacturing of biological products. Coupled with advances in genomics, proteomics, systems biology, and genetic engineering, synthetic biology will offer a toolbox of standardized genetic parts that can be used in the design and production of a new system. The catalyst to new products will be increased understanding of cellular functions and disease models. The catalyst to new products will be increased understanding of both cellular functions and disease models.

B. Concluding Comments

The National Intelligence Manager for Science and Technology in the Office of the Director of National Intelligence asked the Institute for Defense Analyses to identify emerging global trends in advanced manufacturing and to propose scenarios for advanced manufacturing in 10 and 20 years. To do this, we defined advanced manufacturing broadly to encompass all activities related to the development of new products, processes, and business and organizational models. We examined global public investments as a starting point for the selection of technology areas to study (semiconductors, advanced materials, additive manufacturing, and synthetic biology). Our concluding comments follow. These advances will require a labor force capable of utilizing these new methods.

In emerging areas of technology—synthetic biology, advanced materials (specifically, ICME or integrated computational materials engineering), and additive manufacturing—the United States is a leader, but in established areas such as semiconductors, other nations are gaining ground. Although U.S. R&D investments are

the largest in raw-dollar terms, other nations' R&D investments are larger as a percentage of GDP, are growing at a faster rate, or both.

To move advanced manufacturing to new frontiers, science advances are needed, especially interdisciplinary approaches, in multiple areas. Among these are creation of models, databases, and tools for rapid integration of new methods and materials; increasing the quality and availability of materials for additive manufacturing; and increasing fundamental knowledge of genetics, bioengineering, standardization, and predictability of working with complex genetic circuits.

Although the increasing automation of the manufacturing sector will likely lead to the continued decline of this sector as a share of GDP and employment, a strong manufacturing sector will continue to complement a strong service sector, supporting communications, engineering, medicine, and other professional services. However, challenges will remain, including the high cost and risk of conducting R&D for advanced manufacturing and the long time required to bring new materials, products, processes, to market.

Appendix A.

Experts Interviewed

Table A-1. Names and affiliations of experts interviewed, by technology area.

Name	Category	Affiliation
<i>Manufacturing (general)</i>		
Bill Bonvillian	Academic	Massachusetts Institute of Technology
Julie Chen	Academic	University of Massachusetts, Lowell
Tai Ming Cheung	Academic	University of California, San Diego, Institute on Global Conflict and Cooperation
Carl Dahlma	Academic	Georgetown University
Kornel Ehmann	Academic	Northwestern University
Dieter Ernst	Academic	East-West Center
Jay Lee	Academic	University of Cincinnati
Shreyes Melkote	Academic	Georgia Institute of Technology
Sanjay Sarma	Academic	Massachusetts Institute of Technology
Rajan Suri	Academic	University of Wisconsin, Madison
George Whitesides	Academic	Harvard University
Khershed Cooper	Government	Naval Research Laboratory
Kevin Lyons	Government	National Institute of Standards and Technology
Steve McKnight	Government	National Science Foundation
Anonymous	Government	Intelligence Advanced Research Projects Activity
Matthew Roberts	Government	United States Information Technology Office in China
Anonymous	Industry	—
Luana Iorio	Industry	General Electric
Stuart Weitzman	Industry	Eastman Chemical Company
<i>Additive Manufacturing</i>		
David Bourell	Academic	University of Texas
Denis Cormier	Academic	Rochester Institute of Technology
Matthew Frank	Academic	Iowa State University
Neil Hopkinson	Academic	University of Loughborough
Ming Leu	Academic	Missouri University of Science and Technology
Hod Lipson	Academic	Cornell University
David Rosen	Academic	Georgia Tech University
Wei Sun	Academic	Drexel University
Brent Stucker	Academic	University of Louisville
Ryan Wicker	Academic	University of Texas-El Paso

Name	Category	Affiliation
Bill Frazier	Government	Naval Air Systems Command
George Hazelrigg	Government	National Science Foundation
Mary Kinsella	Government	Air Force Research Laboratory
Andy Christensen	Industry	Medical Modeling, Inc.
Kevin Slattery	Industry	Boeing
Terry Wohlers	Industry	Wohlers Associates, Inc.
Advanced Materials		
Anonymous (2)	Government	—
William Joost	Government	Department of Energy
Suveen Mathaudhu	Government	U.S. Army Research Office
Ben Schrag	Government	National Science Foundation
J.P. Singh	Government	U.S. Army International Technology Center-Pacific
David Warren	Government	Oak Ridge National Laboratory
Doug Queheillalt	Industry	Cellular Materials International, Inc.
Robert Schafrik	Industry	GE Aviation
ICME		
Catherine Brinson	Academic	Northwestern University
Richard LeSar	Academic	Iowa State University
Greg Olson	Academic	Northwestern University
Tresa Pollock	Academic	University of California, Santa Barbara
Anonymous	Industry	—
Stephen Christensen	Industry	Boeing
Synthetic Biology		
Anonymous (6)	Academic	—
Adam Arkin	Academic	Berkeley University
Peter Carr	Academic	Massachusetts Institute of Technology Lincoln Laboratory
Anonymous (3)	Government	—
Bob Balcerzak	Government	Chesapeake PERL
George Buchman	Government	Chesapeake PERL
Günter Jagschies	Government	GE Healthcare Life Sciences
Theresa Good	Government	National Science Foundation
Anonymous (3)	Industry	—
David Berry	Industry	Flagship Ventures
Semiconductors		
David DiVincenzo	Academic	RWTH Aachen University
Rajesh Gupta	Academic	University of California, San Diego
Konstantin Likharev	Academic	The State University of New York
Jan Rabaey	Academic	University of California, Berkeley

Name	Category	Affiliation
Josh Alspector	FFRDC	Institute for Defense Analyses
Brian Cohen	FFRDC	Institute for Defense Analyses
Bob Leheny	FFRDC	Institute for Defense Analyses
Chong Ong	Government	Office of Naval Research – Global
Sydney Pope	Government	Office of the Secretary of Defense
Mikhail Rocco	Government	National Nanotechnology Initiative
Robert Trew	Government	National Science Foundation
Anonymous (2)	Industry	—
Bob Doering	Industry	Texas Instruments
Dan Herr	Industry, consortium	Semiconductor Research Corporation (SRC)
Raj Jammy	Industry, consortium	Semiconductor Manufacturing Technology (SEMATECH)
Celia Merzbacher	Industry, consortium	Semiconductor Research Corporation (SRC)
Dev Pillai	Industry	Intel Corporation
Tom Theis	Industry	IBM
Jeff Welser	Industry, consortium	Nanoelectronics Research Institute

Note: For anonymous entries, the number in parenthesis indicates the number of anonymous interviewees in that category (e.g., government).

Appendix B.

Advanced Manufacturing Definitions

The following definitions were reviewed and used as background for deriving the definition of “advanced manufacturing” in Chapter 1, sorted by date of publication from most recent to oldest.

Table B-1. Definitions of advanced manufacturing from multiple sources.

Advanced Manufacturing Definitions	Source	Year
An entity that “[m]akes extensive use of computer, high precision, and information technologies integrated with a high performance work force in a production system capable of furnishing a heterogeneous mix of products in small or large volumes with both the efficiency of mass production and the flexibility of custom manufacturing in order to respond rapidly to customer demands.”	Paul Fowler from the National Council for Advanced Manufacturing, http://www.whitehouse.gov/sites/default/files/microsites/ostp/advanced-manuf-papers.pdf	2010
Advanced manufacturing includes the development of sophisticated processes and technologies that can't easily be replicated. “Advanced manufacturing is most commonly referenced as the use of high-tech processes, often involving factory automation, or the development of innovative products. Nanotechnology, direct digital fabrication and micro manufacturing are a few of the technologies that fit into the advanced manufacturing category...says Shreyes Melkote, engineering professor and interim director of Georgia Tech's Manufacturing Research Center.”	Jonathan Katz, “Advanced Manufacturing: Where is America Today?” <i>Industry Week</i> , September 22, 2010, http://www.industryweek.com/articles/advanced_manufacturing_where_is_america_today_22772.aspx , and Shreyes Melkote, engineering professor and interim director of Georgia Tech's Manufacturing Research Center.	2010
“Advanced manufacturing must entail high-performance computing (HPC) for modeling, simulation, and analysis”	“U.S. Manufacturing—Global Leadership Through Modeling and Simulation,” White Paper, Council on Competitiveness, 4 March 2009, available at http://www.compete.org/images/uploads/File/PDF%20Files/HPC%20Global%20Leadership%20030509.pdf .	2009

Advanced Manufacturing Definitions	Source	Year
A distinction between those sectors that are seen as traditional manufacturing (e.g., automotive and steel industry) and other sectors (e.g., aerospace, medical devices, pharmaceuticals) in three ways: (1) volume and scale economics, (2) labor and skill content, and (3) the depth and diversity of the network surrounding the industry.	"Reexamining Advanced Manufacturing in a Networked World: Prospects for a Resurgence in New England," New England Council, December 2009, http://www.newenglandcouncil.com/assets/rep_2010.01.14_AdvancedManufacturing1.pdf .	2009
"[I]ndustries that increasingly integrate new innovative technologies in both products and processes. The rate of technology adoption and the ability to use that technology to remain competitive and add value define the advanced manufacturing sector."	Virginia Beach Department of Economic Development, 2010. Advanced Manufacturing [cited April 11 2010], www.yesvirginiabeach.com/business-sectors/pages/advanced-manufacturing.aspx .	2010
"AMT [Advanced Manufacturing Technologies] are a group of computer-based technologies including: computer-aided design, robotics, group technology, flexible manufacturing systems, automated material handling systems, storage and retrieval systems, computer numerically controlled machine tools, and bar-coding or other automated identification techniques."	Jennifer C. Percival and Brian P. Cozzarin, "Complementarities in the implementation of advanced manufacturing technologies," <i>Journal of High Technology Management Research</i> 21 (2010): 122–135.	2010
AMTs provide a variety of operational benefits, which include better coordination between different departments; greater control of the processes; reduced product design time; shorter lead time; and stable, high-quality outputs.	Honggeng Zhou, G. Keong Leong, Patrik Jonsson, and Chee-Choung Sum. "A comparative study of advanced manufacturing technology and manufacturing infrastructure investments in Singapore and Sweden," <i>Int. J. Production Economics</i> 120 (2009): 42–53.	2009
"AMT literature generally agrees that it has been widely defined as a group of computer-based technologies, which include computer-aided design (CAD), computer-aided manufacturing (CAE), manufacturing resources planning (MRPII), robotics, group technology, flexible manufacturing systems (FMS), automated materials handling systems, computer numerically controlled (CNC) machine tools, and bar-coding or other automated identification techniques."	Azamawani Abd Rahman, "Buyer-Supplier Relationships in Advanced Manufacturing Technology Acquisition and Implementation in Malaysia," <i>Int. Journal of Economics and Management</i> 2(1) (2008): 95–126.	2008

Advanced Manufacturing Definitions	Source	Year
Advanced manufacturing involves those industries that utilize advanced manufacturing technology or high technology as the main means of production, adopt a modern management pattern, provide high economic reward, optimize an industrial structure, and are capable of sustaining development. From this definition we can find that the characteristics of advanced manufacturing mainly include the following three characteristics: (1) technology is advanced; (2) management is advanced; and the (3) development model is advanced. According to these characteristics, the index system for developing advanced manufacturing is established.	Zhi Hua Wang, "Choosing the industries for developing the advanced manufacturing in Jiangsu Province," <i>Proceedings of 2007 IEEE International Conference on Grey Systems and Intelligent Services</i> , November 18-20, 2007, Nanjing, China.	2007
"AMT involves new manufacturing techniques and machines combined with information technology, microelectronics and new organizational practices in the manufacturing process."	K. L. I. Teng and A. Seetharaman, "Towards a better manufacturing sector: A perspective on the implementation of Advanced Manufacturing Technology in Malaysia," <i>International Journal of Management Science</i> 20 (2003): 490–496.	2003
Advanced manufacturing technology includes "computer-aided design, computer-integrated manufacturing and just-in-time systems."	Annette Baines and Kim Langfield-Smith, "Antecedents to management accounting change: a structural equation approach," <i>Accounting, Organizations and Society</i> 28 (2003): 675–698.	2003
"Advanced manufacturing as the insertion of new technology, improved processes, and management methods to improve the manufacturing of products"	"Advanced Manufacturing Industry Study," National Defense University, 2002.	2002
"AMT is a key enabler to help manufacturers meet the productivity, quality, and cost reduction demands of competitive global markets."	Industry Canada, "What is AMT?" 12 June 2002. Retrieved August 8, 2002, from http://strategis.ic.gc.ca/sc_indps/sam/engdoc/sam_hpg.html (Note: Although the website has been archived, contact information is provided.)	2002
"In general AMT is defined as an application of computer-enhanced, applied science to a firm's production systems."	M. Tracey and C. L. Tan, "Empirical analysis of supplier selection and involvement, customer satisfaction, and firm performance," <i>Supply Chain Management: An international Journal</i> 6 (2001): 174–188.	2001

Advanced Manufacturing Definitions	Source	Year
"AMT are the main technical components of Computer Integrated Manufacturing (CIM) systems... The main feature of CIM is the total integration of all manufacturing functions, including design, engineering, planning, control, fabrication, and assembly etc. through the use of computers. So CIM is a comprehensive measure of computerised integration and information sharing in a manufacturing system."	Hongyi Sun, "Current and future patterns of using advanced manufacturing Technologies," <i>Technovation</i> 20 (2000): 631–641.	2000
AMT can also be grouped "into four dimensions: information exchange and planning technology, product design technology, low-volume flexible automation technology, and high-volume automation technology."	S. Kotha and P. Swamidass, "Strategy, advanced manufacturing technology and performance: Empirical evidence from US manufacturing firms," <i>Journal of Operations Management</i> 18(3) (2000): 257–277, and P. Swamidass and S. Kotha, "Explaining manufacturing technology use, firm size, and performance using a multidimensional view of technology," <i>Journal of Operations Management</i> 17(1) (1998): 23–27.	2000, 1998
AMT is "a comprehensive collection of technologies for enhancing the efficiency and flexibility of manufacturing systems."	Y. Park, "National systems of Advanced Manufacturing Technology (AMT): Hierarchical classification scheme and policy formulation process," <i>Technovation</i> , 20 (2000): 151–159.	2000
"Advance manufacturing technology has different meanings in different situations, but it can be broadly defined as 'an automated production system of people, machines and tools for the planning and control of the production process, including the procurement of raw materials, parts, components and the shipment and service of finished products.'"	C. M. McDermott and G. N. Stock, "Organizational culture and advanced manufacturing technology implementation," <i>J. Operational Manage.</i> , 17 (1999): 521–533.	1999
"AMT can be described as a group of computer-based technologies, including Computer-Aided Design (CAD), robotics, Flexible Manufacturing Systems (FMS), Automated Materials Handling Systems (AMHS), Computer Numerically Control (CNC) machine or other automated identification techniques."	M. H. Small and M. M. Jasin, "Advanced manufacturing technology: Implementation policy and performance," <i>J. Operational Manage.</i> , 15 (1997): 349–370.	1997

Advanced Manufacturing Definitions	Source	Year
AMT can "describe a variety of technologies like CAD and Electronic Data Interchange (EDI) which primarily utilize computers to control, track, or monitor manufacturing activities, either directly or indirectly. In addition, several technologies or programs such as bar codes or group technology which do not directly involve computers are also considered to be AMTs since they are closely associated with other AMT technologies."	K. K. Boyer, G. K. Leong, P. T. Ware, and L. J. Krajewski, "Unlocking the potential of advanced manufacturing technologies," <i>J. Operational Manage.</i> 12 (1997): 331–347.	1997
"Advanced manufacturing technology is defined as computer-controlled or micro-electronics-based equipment used in the design, manufacture or handling of a product.... "Typical applications include computer-aided design (CAD), computer-aided engineering (CAE), flexible machining centres, robots, automated guided vehicles, and automated storage and retrieval systems. These may be linked by communications systems (factory local area networks) into integrated flexible manufacturing systems (FMS) and ultimately into an overall automated factory or computer-integrated manufacturing system (CIM)."	<i>OECD Frascati Manual</i>, Fifth edition, 1993, Annex 2, para. 35, p. 117. http://stats.oecd.org/glossary/detail.asp?ID=52	1993
AMT is "a group of integrated hardware-based and software-based technologies, which if properly implemented, monitored, and evaluated, will lead to improvement in the efficiency and effectiveness of the firm in manufacturing a product or providing a service."	M. A. Youssef, "Getting to know advanced manufacturing technologies," <i>Industrial Engineering</i> 24 (1992): 40–42.	1992
AMT are the "new technologies which are used directly by the firm in the production of a product."	Hamid Noori, <i>Managing the dynamics of new technology: Issues in manufacturing management</i> (Englewood Cliffs, N.J.: Prentice Hall, 1990).	1990

Appendix C.

Public Global Investments in Manufacturing-Related R&D by Selected Countries

This appendix describes the methodology used to construct Table 1 in Chapter 3.

Methodology

To capture global public investments in emerging technologies and manufacturing-related R&D for specific countries and region of interest, we used a bottom-up approach to gather information, drawing on government documents from countries of interest (all open source) that detail public spending on relevant science, technology, and manufacturing programs for current years and into the future. Long-term government plans (such as 10-year plans) were analyzed with special interest as they provide insights into the strategic priorities of specific countries. Using publicly available documents and website information (cited below), we identified 36 programs and initiatives. *This is not a comprehensive listing, but does identify emerging trends.*

Countries and regions selected for the review were the European Union, Germany, the United Kingdom, Japan, China, South Korea, Taiwan, and Brazil.

In an effort to capture the vast array of technology and manufacturing R&D categories in a systematic way, we developed taxonomy to classify areas by major funding thrust, such as information and communication technologies (ICTs), as well as thematic and cross-cutting areas, such as materials and processes for “green” technologies and nanotechnology as a platform technology.

In the European Union, the Framework programs (specifically FP7 initiatives) and the EUREKA Cluster are EU-wide programs that support the R&D areas in our domain. The Intelligent Manufacturing Systems (IMS) Initiative programs have worldwide participation including the EU, the United States, Japan, and Australia.

Germany and the United Kingdom were researched separately because they support significant research in manufacturing infrastructure.

Information for the Asian countries was mostly obtained from the science and technology funding budget allocation by the relevant ministries. The availability of such documents in the public domain is limited, especially for South Korea.

For each program/initiative examined, we identified the areas of technology and manufacturing R&D supported by the program and the funding allocation among the components.

Significant public investments are being made in the following areas of technology R&D:

- Green manufacturing and “low carbon” technologies
 - Displays including organic light-emitting diodes
 - Low power electronics
 - Li-ion and thin film battery technology
 - Photovoltaic cells
 - Materials research for green manufacturing
 - Fuel cell technology
- Nanotechnology as a platform technology
 - Nanomaterials research and instrumentation
 - Packaging
 - Medical applications
- Nanoelectronics
 - Nanoelectronics materials and patterning
 - Nanoimprint (process and equipment)
 - Manufacturing and metrology
- Advanced materials research; modeling and simulation
- Information and communication technologies
 - Printed electronics/roll-to-roll processes
 - Silicon-on-chip, heterogeneous circuits, and embedded systems
 - complementary metal oxide semiconductor (CMOS) and integration with nanoelectronics
 - Integrated photonic circuits
 - Magnetic and other memory technologies
 - Microelectromechanical systems (MEMS) and sensor devices
 - Advanced telecommunication devices

- Transportation and avionics
 - Alternately fueled vehicles
 - Space avionics
- Robotics

Significant public investments are being made in the following areas of manufacturing process R&D:

- Biopharmaceuticals
- Standards
- Tooling and equipment
 - High-performance machinery
 - Modular and adaptable (interoperable) machines
 - Cutting and machining techniques for rapid prototyping equipment manufacture
 - Digital design technologies
 - Computer-aided design (CAD)/computer-aided manufacturing (CAM) tools for design and visualization
- Application of ICT to manufacturing
 - Mass customization (three-dimensional printing, direct digital manufacturing)
 - Virtual organizations
 - Digital manufacturing
- Network-centric production
- Factory-floor and systems integration issues
 - Energy-efficient processes
 - Flexible and robust manufacturing technologies
 - Design platforms for modular, adaptable manufacturing
 - Self-adaptive production lines
 - System modeling and simulation
- Process control and monitoring
 - Sensing and detection

- Process control technologies
- Enterprise-level issues
 - Rapid time-to-market, flexible production logistics, integrated supply-chain platform, data management software (enterprise resource planning, etc.), sales and services.

Our methodology was as follows:

- Funding information was disaggregated by R&D areas for each country. Where program information was at a high level, allocated funds were divided equally among the subareas of the particular sector or focus area. Information presented is for funding per year.
- The larger programs and initiatives are in the European Union (EU). The largest program we identified was the Framework Programme 7 *Nanosciences and Nanotechnologies, Materials & New Production Technologies (NMP)* program, with its focus on integration of technologies for industrial applications, at \$5 billion over 6 years.
- The next largest was the Framework Programme 7 *Joint Technology Initiative on Nanoelectronics Technologies 2020 (ENIAC)*, at \$4 billion, over 5 years.
- In Asia, the investment level is lower, although Japan's *Nanotechnology Project*, part of the 3rd Science and Technology Basic Plan, is large at \$3 billion over 2 years.
- At \$12.5 billion (over 10 years), South Korea's *Battery 2020 Project*, which focuses on lithium battery R&D and production, is also large.
- Taiwan comes next in terms of size with hundreds of millions of dollars of investments in telecommunications, electronic design automation, system-on-a-chip, and nanotechnology.
- Funding information obtained for China covered a broad range of topics, but the funding amounts were smaller compared with those of other countries.

Findings

General

The study team found a total of \$7.9 billion per year in public funding of manufacturing-specific R&D for the select countries/regions. As a benchmark, we estimate public plus private manufacturing R&D to be \$660 billion (based on OECD data, same regions excluding Brazil). Public funding of R&D ranges from 20% to 50% of each nation's total R&D.

For this exercise, the distribution of the investment is more significant than the amount itself. *As expected, the biggest investments are in the fields of ICT and applications of nanotechnology.* Also, beyond the investments in the emerging technologies, factory-floor and systems integration issues attract investment. This indicates the need (and value) of investing in incremental innovation in manufacturing.

There is a significant emphasis on low-carbon technologies in Asia and green manufacturing processes in the EU.

There is considerable emphasis on enabling factors, such as infrastructure support for innovative manufacturing and emerging technologies (e.g., nanotechnology networks established in several countries), as well as on developing international standards for products in emerging areas (such as WiMAX adoption by Taiwan).

Assumptions

Funding priorities of governments serve as a reliable barometer (and useful constraint) of which technology and manufacturing advances will potentially be critical in the short and long term.

In addition to capturing public investment in manufacturing R&D, our review encapsulates government spending on technology R&D as well, since emerging technologies of today will drive the manufacturing advances of the next one to two decades.

Some nations' investments were more opaque than others or available only at the aggregated level; in these cases, we have allocated funds equally among subprograms. Any other caveats associated with the data presented are documented in the appendixes.

Multiyear funding was split into annualized figures and adjusted for purchasing power parity.

Limitations

The biggest limitation in our bottom-up approach was poor availability of data. In particular, a comprehensive list of relevant government funding documents was not always in the public domain. This was especially true for some Asian countries, where we see a mismatch in the country's known technological strengths, and government funding in those areas, from publicly available documents.

In some countries (such as South Korea), government funding is channeled through industry; in these cases, our methodology fails to capture investment unless we broaden our scope to private investments.

Appendix D.

Use of Publication Analysis to Identify Emerging Trends in Semiconductors

We conducted a bibliometric analysis of publications from Web of Science to establish a proof-of-concept methodology for identifying countries with the highest research intensities, chronologically separated into near-, medium-, and far-term time frames. We used data from Thomson Reuters Web of Science between 2000 and 2011.¹ For the semiconductors area, three sets of search keywords were developed (using a combination of literature search and area expertise) to represent areas of research that were being funded for potential commercialization in the near, medium, and far term:

- “More Moore,” which refers to the continued scaling of complementary metal oxide semiconductor (CMOS) technology (5 years out)
- “More-than-Moore,” which integrates different functionality with CMOS technology (10 years out)
- “Beyond Moore,” which explores state variables other than charge (20+ years out)

Table D-1 lists the research topics (keywords) used in these three research areas. The keywords were entered in the Thomson Reuters macro subject categories (Computer Sciences, Engineering, and Materials Sciences) and each of their subcategories (Computer Sciences: hardware and architecture, interdisciplinary applications, engineering electrical, and electronic; Engineering: manufacturing, multidisciplinary, mathematic, including applied and interdisciplinary; and Materials Science: instruments and instrumentation, characterization and testing, multidisciplinary, nanoscience and nanotechnology, and applied physics).

Table D-2 provides the results of the searches, which show country rankings by number of publications for the three different semiconductors-related research thrusts 5, 10, and 20+ years out.

¹ Data downloaded on 20 April 2011 from Web of Science (see http://thomsonreuters.com/products_services/science/science_products/a-z/web_of_science/ for more information).

Table D-1. Research topics (keywords) in three different modalities in the field of electronics—a search on publications in Web of Science.

“More Moore”: post-scaling CMOS process technology (5 years)	“More-than-Moore”: integration of nanodevices with CMOS technology (10 years out)	“Beyond Moore”: exploring state variables other than charge (20+ years)
Photolithography	Nanoelectronic	Spintronic
Extreme ultraviolet	Nanophotonic	Quantum dot
Optical proximity correction	Nanomagnetic	Qubit
Flash memory	Carbon nanotube	Single electron transistor
Phase-change memory	Nanowire	Molecular device
High-K dielectric	Nanoimprint lithography	Molecular computing
Leakage current	Spintronics	Quantum information processing
Silicon-on-insulator	Magnetoresistive Random Access Memory	
Electronic design automation	Spin-torque	

Table D-2. Bibliometric results-counts of publications that include keywords for research extending current CMOS technology (5 years out), research integrating nanoelectronics and CMOS (10 years out), and research exploring options beyond CMOS (20+ years out) (based on data from Thomson Reuters Web of Science for 2000 to 2011).

Research extending current CMOS technology			Research integrating nanoelectronics and CMOS			Research exploring options beyond CMOS	
Country	Pubs		Country	Pubs		Country	Pubs
USA	4790		USA	15132		USA	8889
Japan	2800		China	13166		Japan	3478
South Korea	1995		Japan	6031		China	3261
China	1878		South Korea	4607		Germany	2969
Taiwan	1563		Germany	3301		UK	2029
Germany	1186		UK	2472		France	1712
France	1094		Taiwan	2439		South Korea	1377
UK	851		France	2354		Italy	1271
Italy	803		India	1981		Taiwan	1128
Belgium	621		Singapore	1522		Canada	958
India	592		Italy	1431		India	953
Singapore	586		Spain	1173		Russia	916
Spain	391		Canada	1095		Spain	756
Canada	348		Australia	985		Netherlands	595
Russia	262		Russia	933		Switzerland	550
Switzerland	236		Switzerland	737		Singapore	535
Netherlands	215		Sweden	734		Sweden	506
Sweden	205		Belgium	601		Poland	505
Australia	170		Netherlands	564		Australia	498
Greece	166		Brazil	531		Israel	406
Poland	161		Iran	526		Brazil	398
Finland	153		Poland	501		Belgium	318
Israel	137		Israel	430		Austria	285
Brazil	126		Ireland	427		Finland	244
Ireland	116		Mexico	369		Ukraine	219

Source: Data downloaded on April 20, 2011, from Thomson Reuters Web of Science.

The United States leads the sector at each of the time frames, but countries such as South Korea and Taiwan, which are manufacturing powerhouses today, lead in the short term but fall in ranking over the longer term. Research leaders Japan and, increasingly, Germany and other EU countries along with China, move up in ranking. This methodology of categorizing keywords allows for a time-differentiated bibliometrics-based (publications) study of emerging fields.

Appendix E.

Innovation Policies and Other Factors that Affect Manufacturing in Six Countries

Introduction

This appendix provides an overview of government structures, overall innovation strategies, and defense industries of Brazil, China, Germany, Japan, the Republic of Korea, and the United Kingdom. The countries profiled were chosen because of their current and potential capacity for advances in manufacturing (the United Kingdom, Germany, Japan, and Korea) or because of their emerging capabilities (China and Brazil). We used categories proposed by Deloitte Council on Competitiveness as a guide for examining innovation challenges and policies in each of the countries examined (see Table E-1). These categories are indicators of a country's capacity to undertake advances in manufacturing.

Most of the six countries have been affected by the economic downturn, and they struggle to encourage investment from government, private, or foreign direct investors. A few have responded by increasing nonmonetary incentives (tax breaks or intellectual property) or by increasing efficiency of the innovation process (streamlined regulations), and most provide additional support for small and medium enterprises (SMEs).

Another common problem was lack of an adequate workforce supply. Many countries have an aging population. Educating a new workforce in sufficient numbers and quality is necessary in fields that meet future industry needs. The need to secure resources, typically energy and rare-earth materials, is a third common problem.

Some countries have ensured multiple resource streams, while others have decreased or replaced the use of limited resources. Finally, each country is working to strengthen technology transfer or linkages between at least two of four actors (academia, private sector, government, and international), although the particular connection of focus varied by country. Table E-2 summarizes each country's status in terms of common challenges to manufacturing innovation (investment, workforce, materials and energy, and linkages).

Table E-1. Categories used to examine capacity for manufacturing innovation.

	Talent-driven innovation	Capital, labor, and materials	Energy cost and policies	Physical infrastructure
Input	• Labor force quality, number • Researcher quality, number • Businessperson quality, number • Manufacturing “know-how” • Immigration policy	• Cost of materials • Cost of labor • Availability of raw materials	• Cost of energy • Energy policies • Sustainability policies	• Facilities’ quality, number • Communications network
	Government investment	Regulatory environment	Economic, trade, and financial systems	
Policy Framework	• Emphasis on investments in manufacturing • Investments in science, technology and innovation • Public-private partnerships • Connections between actors • Health care	• Legal and regulatory environment • Regulatory compliance cost, time • Labor law and regulation • Transparency, stability	• Tax system • Trade policy • Bank and economic policies • Intellectual property	
	Business dynamics	Supplier network		
Market Environment	• Antitrust laws, technology transfer, and regulations • Intensity of competition • Foreign direct investment • Health of economic and financial system	• Availability of qualified supplier base • Quality control		

Table E-2. Examples of policies for commonly cited challenges to manufacturing innovation.

Challenge	Country summary	Example policies
Investment	• Brazil: foreign direct investment high, government and business low • China: Overall strong • Germany: Private strong, low equity, start-ups, and venture capital • Japan: Total and private strong, low start-up and foreign direct investment rates • Korea: Total and private strong, low foreign direct investment, lower venture capital • United Kingdom: Overall strong, strong equity	2007–2010 Action Plan on Science, Technology and Innovation for National Development I (PACTI) requires funding from private sectors; Science and Technology Sectoral Funds in 1999 requires funds from those using resources from select productive sectors (Brazil) (NRC 2010)
		China Banking Regulatory Commission issued the Guidance on Bank Loan Business to Small Enterprises to expand firms' access to venture capital (China) (Pro INNO Europe 2009).
		New Japan External Trade Organization (JETRO) has "re-invented" its organization from an export-promotion agency to a national economic development organization that is seeking to attract foreign direct investment (Japan) (European Union 2011).
Workforce	• Brazil: young, inexpensive, low graduation rate, pool in academia • China: Low quantity of workers, high graduation rate, "brain drain" • Germany: Well educated, sufficient quantity of workers, few Ph.Ds. • Japan: Well educated, low quantity of workers • Korea: aging, high graduation rate, many "non-regular" workers • United Kingdom: Tertiary graduates high, graduates in certain sectors low	Pays half the salaries of Ph.D. researchers for their first three years of employment in industry (Brazil) (NRC 2010).
		Participates in international partnering through Erasmus Mundus, ALFA, and IRSES to fund scholarships for Brazilian undergraduate and postgraduate students and may entail capacity-building for universities (Brazil). (CREST OMC Working Group 2008)
		Additional employer-led National Skills Academies, which includes: manufacturing, nuclear, process and environmental technologies, IT, materials academies (United Kingdom) (National Skills Academy 2008).
		Increase funding for the Train to Gain vocational training to employed individuals, the establishment of a UK Commission for Employment and Skills; support very high cost and "vulnerable" science subjects strategically important but with relatively low student demand (United Kingdom) (European Union 2011).
Materials and energy	• Brazil: Exporter, energy sufficient • China: Materials, energy concern • Germany: Not mentioned, strong renewable energy sector • Japan: Materials, energy concern • Korea: Materials, energy concern • United Kingdom: Materials, energy concern	Reserve domestic resources, general tariffs, decreased quotas, and other trade policy to restrict export of resources (China) (Miller and Areddy 2011).
		The Renewable Energies Act, the Energy Saving Ordinance, Act on Heating Through Renewable Energy, etc. provide additional incentives (Germany) (Pro INNO Europe 2009).
		Develop alternative technologies that do not use rare materials (Japan) (NRC 2010).
		Top Cluster Program, or Leading Edge Cluster Competition, to fund clusters in thematic, interdisciplinary areas determined "bottom up" through competitive funding rounds (Germany).
Linkages	• Brazil: Many policies in this area • China: Government-industry strong, academic-industry weaker • Germany: Strong academic-industry • Japan: Academic-industry weaker • Korea: Private sector relies on own research, university minor role • United Kingdom: Difficulty translating knowledge into "new-to-market products"	MKE provided Technological Development Program for Industrial Innovation and Regional Technology Innovation. SMBA provided Collaborative Technology Development for Industry-Academia-Research Linkage (433 million euro). These promote collaborative technological development through Industry-Academia-Research Linkage (South Korea) (European Union 2011).
		Each Government Department will include an Innovation Procurement Plan as part of its Commercial Strategy, setting out how it will drive innovation through procurement and use innovative procurement practices (United Kingdom) (UK Department for Business Innovation and Skills 2008)

Common areas of investment were energy, information technology, biotechnology, and nanotechnology. Germany and South Korea specifically target manufacturing technologies as an area for future research investment. The sections that follow provide more detail.

Based on investment goals, South Korea seems to most aggressively plan for increased defense-related industry capacity. Brazil, which has historically contracted services, now shows more interest in a domestic capacity, with increased research investment and new partnerships related to security technologies. Satellite technology was a common area for defense-related investment. Brazil, China, and South Korea plan to strategically invest in defense technologies as well; each cite nuclear technology as an area for future investment.

Brazil

Manufacturing Innovation Structure

Brazil's Ministry of Science and Technology (MCT) oversees the funding and policy agency FINEP (Research and Projects Financing).¹ FINEP implements, manages, and operates innovation programs following MCT policy and in close cooperation with the agency funding basic research, the National Council for Scientific and Technological Development (CNPq).² The Ministry of Development, Industry and Foreign Trade (MDIC), is responsible for defining and coordinating Brazil's industrial policy through the recently created Brazilian Agency for Industrial Development (ABDI). MDIC also has oversight of the major Brazilian Development Bank (BNDES), which has innovation financing programs. Brazil has a young, emerging innovation system with strong growth potential (Pro INNO Europe 2009). Brazil is the largest economy in South America and GDP growth has averaged 4% over the last decade. This growth is the result of international demand for their manufactured goods and other commodities (natural resources) which has spurred the growth of their middle class. They have implemented several policy reforms focused on reducing inflation and fostering growth (Meyer 2011).

Although Brazil has had a strong manufacturing presence, it has historically been in low-tech sectors (Deloitte Council on Competitiveness 2010). New policy still focuses on creating authorities and regulation for innovation. Brazil continues to build a unique, decentralized innovation policy, with programs delegated to the states. In January 2009, the Inter-Ministerial Committee on the Legal Framework of the Innovation Law

¹ Financiadora de Estudos e Projetos, also known as the Brazilian Innovation Agency, is a publicly owned company subordinated to the Ministry of Science and Technology (MCT).

² Conselho Nacional de Desenvolvimento Científico e Tecnológico provides scholarships and grants to individuals and research groups.

convened for the first time to propose changes to and refine the Innovation Law (2004) and the Good Law (2005). Pro-INNO has argued that the strategy process is not transparent or demand-driven. Several policies are restricted to just those industry sectors that Brazil considers strategic.³

Brazil has historically given priority to the development of its manufacturing sector and to promoting domestic production through an escalated tariff structure (World Trade Organization 2009). Recent policy themes are to change firm investment and patenting behaviors, increase resources, and ensure even development across geographic sectors. The range of measures to promote and sustain the creation and growth of innovative enterprises has been strengthened, particularly for risk capital, sectoral innovation in manufacturing, innovation in services and innovative start-ups. Some policies promote specific sectors.

Brazil tends to partner to support its defense-related industry and has recently increased defense spending. Brazil's current defense-procurement programs support local industry, but through foreign contractors that operate manufacturing facilities in Brazil. Italian vehicle company Iveco; multiple French contracts including ship and helicopter manufacturers; 2008 Russian contract for aerospace, nuclear and defense industries; Israel's defense electronics company Elbit Systems and UAV prime Israel Aerospace Industries; 2010 UK contract for frigate acquisition (PakPasban 2011). The April 2010 comprehensive defense cooperation agreement (DCA) with the United States includes research (U.S. Department of State 2010; Raza 2011).

Innovation Strengths and Weaknesses

Brazil's innovation policy is emerging; it has the necessary materials and people, but has not yet realized growth in the number of large firms. Areas of industry strength are motor vehicles, agricultural, deep-sea oil production, biotechnology, and remote sensing. Attempts to build a nanotechnology industry are based on investment strategies, special incentive funds, and patenting activity in this area. The FUNTEC-Technology Fund supports strategic areas: renewable energy, environment (control cars and plants emissions), electronics (microelectronics, nanotechnology, and displays), new materials (new metal materials and advanced ceramics), and chemistry (Pro INNO Europe 2009). Areas of future investment, which are outlined in Table E-3, include technologies for launching rockets and satellites and enriching uranium (NRC 2010).

³ Examples include PROFARMA, which funds the pharmaceutical industry (Anonymous 1 on Semiconductors); FUNTEC-Technology Fund, which targets electronics, new material, renewable energies, nanotechnology, and chemistry (Anonymous 2 on Semiconductors 2011); and BNDES Pro-Engineering (PRO-Engenharia), a program for automotive, capital goods, defense, nuclear, aeronautics, aerospace, and oil and gas suppliers' chain.

Table E-3. Brazil's current leading industry sectors and areas of investment.

Current leading industry sectors	Areas of investment
• Textiles, shoes • Chemicals • Cement • Lumber, iron ore • Tin, steel • Aircraft, motor vehicles and parts • Other machinery and equipment • Agricultural • Deep-sea oil production • Biotechnology • Remote sensing	• Information technologies • Health supplies • Biofuels • Electrical power, hydrogen, and renewable energy • Oil, gas, and coal • Agribusiness • Biodiversity and natural resources • Amazon and the semi-arid region • Weather and climate change • Space program • Nuclear program • National defense and public safety

Sources: CIA (2011) and NRC (2010)

Brazil's workforce is young, growing, and becoming increasingly educated, but its few graduates are pooled in the academic arena rather than industry. While Brazil has built an education infrastructure, the percentage of its population with tertiary education in OECD countries is still one of the lowest. To encourage transfer to the private sector, Brazil pays half the salaries of Ph.D. researchers in their first 3 years of employment in industry.

Brazil has natural resources; energy independence; and a well-established, diverse industrial base and financing system. Many countries are investing in Brazil. Brazil also has strength in international cooperation, with more patents with foreign co-inventors than the OECD average (OECD 2010b). On the other hand, Brazil has lower patent and publication rates compared with similar countries, and is a net importer of intellectual property. While Brazil once had looser intellectual property laws, but the World Trade Organization now scores Brazil as having strong intellectual property laws, although the processing time to obtain a patent still takes an average of 7 years. Brazil has a low percentage of GDP investment in research, and business investment in R&D is half that of similar countries. According to the World Bank, Brazil ranks below Mexico and Greece in terms of ease of doing business (OECD 2010c; World Bank 2011).

Further, investment in research is low, and it can take over a year to receive funds. To address this problem, Brazil has created policy levers for increased industry and state investment. The country's Action Plan on Science, Technology and Innovation for National Development (PACTI) goals includes an increase in national spending on research, development, and innovation (RD&I) from 1.02% of GDP in 2006 to 1.5% of GDP in 2010. Brazil has begun to require industry to fund research through the 2007–2010 PACTI, and Brazil gathers and redirects funds from taxes on resource use. Brazil's funding distribution is directed toward even geographic development and strategic

research priorities. Decentralization of funding has led states within Brazil to invest in innovation policy, research, and new infrastructure to participate in state-level programs.

Brazil has a suite of programs to target financial aid and increase alternative incentives to industry. The INOVAR and the Economic Subsidy program offer early development and small business investment; the Inter-American Development Bank provides seed money.

Brazil also creates markets to encourage technology transfer. The INOVAR PROJECT was launched in May 2000 as a strategic action of FINEP. Its aim is to promote the development of small- and medium-size technology-based businesses by designing instruments for their financing, especially venture capital.⁴ PROINFA offers guaranteed contracts, for example. The main, government-led bank in Brazil cut financing rates in 2009 and is increasing innovation finance programs to increase ease of doing business, although some measures are sector-specific (Table E-3).

Table E-4 provides examples of Brazilian policies in key innovative strategies.

⁴ See http://www.venturecapital.gov.br/vc_n ing/en oquee PI.asp.

Table E-4. Selection of recent Brazilian policies within innovation categories.

Key challenges as identified by reports	Examples of policies that address challenges
Graduate distribution	Pays half the salaries of Ph.D. researchers for their first 3 years of employment in industry (NRC 2010)
Low tertiary education	Participates in international partnering through Erasmus Mundus, ALFA, and IRSES to fund scholarships for Brazilian undergraduate and postgraduate students and may entail capacity-building for universities (CREST OMC Working Group 2008).
Energy and sustainability	See “Creating a Market.” Policies to create a market include renewable energies.
Low investment by the government	Economic Subsidy program gives direct non-reimbursable aid for firms to invest in innovation (implemented by FINEP (Pro INNO Europe 2009). Fill in early stage financing gaps to technology-based start-up firms with the Prime program (Pro INNO Europe 2009). Venture capital and other instruments through FINEP and FNDCT (Pro INNO Europe 2009). INOVAR co-funded by government institutions like K and FNDCT and Inter-American Development Bank to provide seed money. Website to facilitate access to financing mechanisms (Bleviss 2010).
Low investment by industry	The Science and Technology Sectoral Funds come from taxes on businesses using natural resources, from Excise Tax and the Contribution for Intervention in the Economic Domain (CIDE) (Brasil.gov 2010). Productive Development Program (PDP) goal to raise private business research and development (R&D) expenditures to 0.65% of gross domestic product (GDP) (Pro INNO Europe 2009). Science and Technology Sectoral Funds in 1999, which are tools to secure and redirect ST&I funding using resources from select productive sectors (NRC 2010).
Tax system	Taxes on businesses using natural resources, from Excise Tax and the Contribution for Intervention in the Economic Domain (CIDE). These are used to reinvest in innovation.
General innovation policy	2009 Legal Framework of the Innovation Law, which has representatives of MCT, MDIC, MF, and MPOG. The Committee’s objectives are to identify, propose changes and refine the Innovation Law (2004) and the Good Law (2005) (Pro INNO Europe 2009). 2009 Permanent Innovation Law Monitoring Committee was established (Pro INNO Europe 2009).
Trade policy	Mercosur trade agreements include cooperative agreements for research (NRC 2010).
Creating a market	PROACOL Program: Supports development of alcohol fuels and biodiesel and vehicles to run on them. Public sector subsidies and tax breaks phased out, financed distribution network established, and fuel mixture set at 25%. Variety of requirements and incentives (Bleviss 2010) PROINFA Program to contract 10% power from small hydro, biomass, and wind producers (Bleviss 2010) Industrialization policy centered on replacing imported manufactured products with Brazilian-made ones, yielding a highly diversified manufacturing sector (Deloitte Council on Competitiveness 2010).
Change business behaviors	Enterprise Innovation Front (Mobilização Empresarial pela Inovação-MEI) with the aim of making innovation a permanent strategy of Brazilian firms; mechanisms still being determined (Pro INNO Europe 2009).

China

Manufacturing Innovation Structure

The People's Republic of China has a Ministry of Science and Technology (MOST). The Chinese government funds research through medium- and long-term plans that split funding into programs by the stage of technology development. The Chinese Academy of Science is the major conduit of funds. Funding is channeled through three programs based on the stage of research (basic, applied, special funds): 863 Program (National High Technology Program), 963 Program (basic research), Support Program (applied R&D; until 2006 formally known as Key Technologies Program), Torch Program (commercialization and S&T industrial parks), Key Laboratories Program, and Engineering Research Centers (Springut, Schlaikjer, and Chen 2011). China recently initiated a Strategic Emerging Industries initiative that targets growth in seven industries (see sidebar in Chapter 4, section C.2.) Table E-5 lists primary industry sectors and areas of investment.

Table E-5. China's current leading industry sectors and areas of investment.

Current leading industry sectors	Areas of investment
• Mining and ore processing • Iron, steel, aluminum, and other metals; coal • Machine building; armaments • Textiles and apparel • Petroleum, cement, and fertilizer • Chemicals • Consumer products: footwear, toys, and electronics • Food processing • Transportation equipment: automobiles, rail cars and locomotives, ships, and aircraft • Telecommunications equipment, commercial space launch vehicles, satellites	• Acquisition of core manufacturing and IT technologies • Nanotechnology • New Materials • Space, Satellite, and Sensor Technologies • Increase in focus on biotechnology • Acceleration of marine technology development • Enhancement of basic science and frontier technology research capabilities, with an emphasis on multidisciplinary research • Development of energy and water resources in conjunction with environmental protection efforts

Source: Current leading industry sectors ranks the country's top industries by value of annual output (CIA 2011). Areas of investment reflect government spending as reported by (NRC 2010).

China uses several innovation strategies. It is most heavily reliant on technology adoption through reverse engineering, foreign direct investment, and purchase of foreign patents. It has also sought to increase its historically strong ability to create “dual use” technology with well-integrated military research organizations (National Academies of Science 2010). However, it is moving to encourage original innovation through an “indigenous innovation” policy (Linton and Hammer 2010). The U.S.-China Economic and Security Review Commission warned of cyber-warfare capabilities that may provide

an asymmetric advantage. But like Japan, China still imports software, with primary suppliers being the United States and India (Homeland Security Newsletter 2011a).

China's innovation and modernization goals rely on access to the global market. China appears to plan to continue its current policy trajectory concerning trade and intellectual property. The 2008 patent law states goals for strategic patents in biology, medicine, information, new materials, advanced manufacturing, new energy, oceanography, resources, environmental protection, modern agriculture, modern transportation, aeronautics, and astronautics (Friedman 2008).

China has a strong armament industry guided by the Military Science and Technology Development Strategy and the Modern Defense Scheme planning documents. China has slowly begun to privatize its defense technologies. Sichuan and Shaanxi, the two regional centers for defense industry, have a number of top-10 enterprises in munitions, heavy chemical engineering, nuclear engineering, aviation, space, new materials, electronics, and general military technology (OECD 2009b). Cybersecurity reports for critical infrastructure show China, Italy, and Japan as leading countries in security, while Brazil (an important resource partner), France, and Mexico are lagging in their security measures (Homeland Security Newsletter 2011c).

Innovation Strengths and Weaknesses

China, which is considered to have a strong and growing innovation system, is ranked by Deloitte above the United States in manufacturing competitiveness (Deloitte Council on Competitiveness 2010). Growth in regional innovation capacity is highly unequal, which is largely intentional to experiment with controlled growth in "special economic zones." China has strategies to address most challenges identified in the literature (with the noted exceptions of trade and intellectual property).

China is emerging as a leader in renewable energy technologies, in particular solar. The main investment strategy outlined by the Chinese Academy of Sciences publication "S&T Roadmap 2050" includes defense technologies (with increased dual-use technologies), nuclear power, and nuclear-waste-processing technology (mainly accelerator-driven systems) (European Union 2011).

China's strengths are its supply of inexpensive labor, large internal market, and high investment, both by the government and through high foreign direct investment (European Union 2011). Science and Engineering degrees, as a percentage of all new degrees, are higher than the OECD average, although the quality of the degrees is often questioned (OECD 2009b).

Chinese weaknesses remain the low number of skilled workers, energy capacity, and access to raw materials. China also has little original research, reflected in fewer first-to-market innovations. China has a "socialist-market economy" that facilitates strong

partnership structures between government and private science and technology entities, in particular with the military. In contrast, China struggles to create ties between academic and private entities (OECD 2009b).

China has multiple policies to improve the size of a skilled workforce, ranging from increased schooling, to reversing the loss of educated population to other countries, to allowing increased collaboration or immigration of a foreign workforce as outlined in its first National Talent Program (Huiyao 2010). The effect of such policies has been limited. There are also high unemployment rates and income disparities. Although there is no clear health-care or insurance requirement, the government has plans to overhaul medical insurance and standardize coverage nationwide (European Union 2011). This effort should greatly affect the cost of labor. China has no policy to reduce income disparity.

China has formed a diversified strategy to secure access to energy and natural resources. Key policies include a massive expansion of alternative-energy sectors (notably hydropower and wind energy). China is already a leader in solar energy. China's resource management of, and trade policies for, raw materials are controversial but unlikely to change. They include securing independent supply chains in other countries.

China is a leading investor in developing countries, has plans to build an industrial port in Brazil and a major railroad (Homeland Security Newsletter 2011b). China also reserves its own resources. China attempted to impose export restrictions on nine raw materials and in general has tariffs, decreased quotas, and other trade policies to restrict export of resources (Miller and Areddy 2011).

Table E-6 provides examples of policies in key innovative strategies.

Table E-6. Selection of recent Chinese policies within innovation categories.

Key challenges as identified by reports	Examples of policies that address challenges
Emigration of workforce "brain drain"	Cheung Kong Scholars Program to recruit professors from abroad (Li Ka Shing Foundation 2010). Recruit general foreign S&T through the Hundred Talents Program (European Union 2011). Target younger overseas population through Spring Lights Program and Chang Jiang Scholars Program, Distinguished Young Scholar Program (Huiyao 2010).
Number of skilled workers	First National Talent Building Plan in 2010 set workforce goals (NRC 2010). Increase education spending to 4% of GDP by 2012 (Wang 2011). The government also set a goal that 100 of its business leaders and chief financial officers be listed in the Fortune 500 by 2020 (Huiyao 2010). 211 program launched by the Ministry of Education in 1995 to construct 100 top universities and key disciplines to promote the development of higher education and enhance performance of science, technology and culture (European Union 2011).

Key challenges as identified by reports	Examples of policies that address challenges
More flexible immigration	Preparing to overhaul immigration policy (Deloitte Council on Competitiveness 2010). Increased hukou registration to allow internal flow of workforce across regions (European Union 2011). State-owned enterprises are recruiting globally for business leaders, and citizenship is not required (Huiyao 2010).
Energy	2010 update to the original 2005 renewable energy law. Included guarantee that electric utilities purchase all renewable power generated and increases to the Renewable energy Fund (Martinot and Jungfeng 2010). 2009 a new feed-in tariff regime was established for wind power based on relative wind resources in four regions. Multiple energy policies enacted since 2008 (Martinot and Jungfeng 2010).
Encourage more innovative research	Foreign investors are required to reward local staff for innovation (Deloitte Council on Competitiveness 2010).
Trade policy	Implementing Policies for the Medium- and Long-term National Plan for S&T Development promulgated in 2006; it is specified that indigenous innovative products are the priority in public procurement and should be given a price advantage; and no less than 60% of the cost of technology and equipment purchase should be spent on domestic firms (European Union 2011; Deloitte Council on Competitiveness 2010). Natural Indigenous Innovation Products (NIIP) grants status to products for preferential procurement based on how domestic the innovation is (Ahrens 2010). 2007 reissued the Regulation of Zero Import Customs Duty on Materials and Equipment Used for Scientific and Education Purpose (European Union 2011).
Tax policy	Dissemination of Science and Technology Knowledge Law (2002) gives tax preference policy. Tax credit is 150% of qualified R&D expenditure for enterprises. Investment on R&D equipment can be excluded from income tax for equipment with a value of less than 300,000 Yuan. Accelerated depreciation is applied to R&D equipment over that (European Union 2011).
Small and medium enterprise (SME) support	Innovation Fund for Small Technology-based Firms (Innofund) is a special government fund in support of technological innovations for small tech-based firms (Pro INNO Europe 2009).
Bank and economic policies	China Banking Regulatory Commission issued the Guidance on Bank Loan Business to Small Enterprises to expand firms' access to venture capital (Pro INNO Europe 2009). Notice of Improving SME Loan and Credit Insurance System provide the legal basis for supporting SME innovation (Pro INNO Europe 2009).
Intellectual property	2008 Compendium of China National Intellectual Property Strategy includes areas for strategic patents (paragraph 16) new technology standards (paragraph 17), and some goals for IP such as courts of appeal for IP cases, but no concrete plans (Friedman 2008).
Foreign direct investment	The business tax rate for Foreign Direct Investment corporations in Special Economic Zones is 15%, whereas the rate for domestic enterprises is 33%. In addition, 40% of the taxes paid by Foreign Direct Investment corporations are refundable on the condition that the funds are reinvested in China over a 5-year period (European Union 2011). Foreign investors are required to reward local staff for innovation and, increasingly, to use technology developed in China (European Union 2011).
Antitrust laws, technology transfer and regulations	Recent anti-monopoly law to break what it considered to be "monopolization" of key technologies by multinationals. This law forces companies to adopt the indigenous innovation regime, thus compelling them to transfer proprietary technologies to their Chinese subsidiaries or risk losing access to procurement by state-owned enterprises (NRC 2010).

Germany

Manufacturing Innovation Structure

In Germany, research funding is split between two ministries, one for innovation policy and industry research (BMW, Federal Ministry of Economics and Technology) and one for federal research funding and policy (BMBF, Federal Ministry of Education and Research). Each of the states, or Länder, has a state version of the two entities. University funding is coordinated through the DFG (German Research Foundation), and non-university funding through other organizations (European Union 2011). The BMBF started a nonprofit professional association called the AiF (German Federation of Industrial Cooperative Research Associations “Otto von Guericke”). It consults with multiple ministries to coordinate industrial research and policy.

A second consulting agent is the Council for Innovation and Growth (Rat für Innovation und Wachstum) of mixed industry, academic, and government membership. The Expert Commission on Research and Innovation is an appointed expert group that evaluated country innovation (Commission of Experts for Research and Innovation 2011).

In order of export quantity, Germany is a leading manufacturer in the automotive sector, electrical engineering, chemicals and pharmaceuticals, and mechanical engineering. Most research and development funding comes from industry for in-house research (OECD 2009a) (OECD 2010c). At present, air and space industry, electrical engineering and manufacturers of data processing equipment, and mechanical engineering receive the most funding (Commission of Experts for Research and Innovation 2011). Germany provides incentives for alternative energy sources and is third in patents for nanotechnology (OECD 2010c).

Table E-7 lists primary German industry sectors and areas of investment.

Table E-7. Germany’s current leading industry sectors and areas of investment.

Current leading industry sectors	Areas of investment
• Iron, steel, coal, cement • Chemicals • Machinery, machine tools • Vehicles, shipbuilding • Electronics • Food and beverages, textiles	• Biotechnology • Nanotechnology • Optical technologies • Microsystem • Materials and production technologies • Aeronautics technology • Information and communication technology

Source: Current leading industry sectors ranks the country’s top industries by value of annual output (CIA 2011). Areas of investment reflect government spending in key technologies as reported by Federal Ministry of Education and Research (2010)

Germany has a strong array of “market pull” strategies to support innovation. These strategies aid start-up companies, have an increasing emphasis on public procurement of new technologies, and use standards to drive innovation (Bleviss 2010). The three government reform initiatives are (1) the Excellence Initiative, which is for interdisciplinary research at designated research centers of excellence and promotes and recruits a highly qualified workforce that is 25% international; (2) the Higher Education Pact, which includes demand-oriented study courses, new funding, and increased first-year students; and (3) the Joint Initiative for Research and Innovation, which is a policy to support institutions that are jointly funded by the federal government and the Länder, including an increase in non-university funding by 5% annually (European Union 2011).

Germany does not historically have a comprehensive defense industrial policy, but recent research priorities indicate that one may be emerging. The majority of arms procurement is through cooperative agreements, and Germany has sought a European integration of defense and production (Centre for European and Asian Studies 2002). However, a recently released High Tech Strategy for Germany includes manufacturing for security technologies supported by an interdisciplinary approach that includes humanities and social sciences. The German government wants to “protect the complex supply systems and communication networks and safeguard global mobility with the help of innovative technologies” (Scientific American 2010).

Innovation Strengths and Weaknesses

Germany has a strong manufacturing innovation system with little growth. It is the third most inventive country in terms of number of patents, after the United States and Japan (OECD 2010c). Certain industries have increased demand, such as Germany’s specialized manufacturing systems (precision machine tools, highly engineered goods, and complementary technical support service) and merging IT and electronics (Deloitte Council on Competitiveness 2010).

Germany has strong standardization and quality control, research infrastructure, and higher education institutions. Weaknesses are a low rate of start-ups, relatively high labor cost, and a shortage of equity capital and venture-capital investment (Commission of Experts for Research and Innovation 2011). Federal expenditures for the manufacturing sector are a relatively large percentage of total expenditures, although government support to business R&D, direct financing of business R&D, and R&D tax subsidy rates are below the OECD average.

The German workforce is well educated, but the levels of Ph.Ds. are low. The suite of programs under the Higher Education Pact has stopped the downward trend in new university entrants (Federal Ministry of Education and Research 2009).

Germany uses systematic foresight strategies and stakeholder input to identify future manufacturing innovation needs, advances in science and technology needed to accelerate innovation, and funding requirements to implement relevant programs. Their recent analysis, called “Production Research 2020” sets forth their Federal funding priorities (O’Sullivan 2011; Federal Ministry of Education and Research 2011).

German industries are highly specialized, medium-tech, with low growth potential. Germany is interested in expanding its manufacturing base. The High-Tech Strategy for Germany, which forms the plan for this, includes increased investment in security, health, mobility, and climate protection (Federal Ministry of Education and Research 2011). To encourage higher technology manufacturing, the BMBF had the Top Cluster Program, or Leading Edge Cluster Competition, fund clusters in thematic areas determined “bottom up” through competitive funding rounds. Winning clusters were in autonomous logistics services, medical technologies (including intelligent sensors), microsystems, biotechnology, software, organic electronics, aviation, and energy efficiency.⁵ To maintain their manufacturing skills and employment during the recent downturn, they reduced working hours and emphasized cross training (Möller 2010).

Multiple reports identified policies to increase the rate of start-ups and to improve the conditions for starting up innovative enterprises, especially in access to capital. Bank loans are not typically used for financing, and most innovation projects are considered “non-bankable” risk and thus outside the scope of credit financing. The German Ministry of Education and Research (BMBF) launched a new measure to validate funding to increase use of academic research results in commercial ventures, and the KMU-innovative program simplifies small and medium enterprise access to funds, including simplified credit risk assessment.

Many programs increase access to capital, especially for small and medium enterprises. However, new policies also impose regulations for standards and restrictions regarding forms of finance. The European Commission’s Alternative Investment Fund Managers (AIFM) Directive imposes new standards on alternative sources of funding, which some worry will have a protectionist effect (Baker 2011).

Table E-8 provides examples of policies in key innovative strategies.

⁵ See *Strengthening Germany’s role in the global knowledge society* at <http://www.bmbf.de/en/6443.php>.

Table E-8. Selection of recent German policies within innovation categories.

Key challenges as identified by reports	Examples of policies that address challenges
Access to capital	The Act on Modernisation of the Framework for Private Equity Investors and the Act for the Promotion of Venture Capital Investments were intended to improve the framework condition for venture-capital investment into innovative firms (Pro INNO Europe 2009). New loan program to promote start-ups (KfW Start-up Money) with lower interest rates (Pro INNO Europe 2009). High-tech Start-up Fund and “EXIST” program (www.exist.de); business start-up grant for new entrepreneurs funds: living expenses for 1 year, coaching, materials, and equipment (Rammer 2007). ZIM, the central innovation program for SMEs, offers more flexible funding of R&D projects conducted by SMEs, including funding for single projects, cooperative projects, personnel exchange, and the management of networks (Pro INNO Europe 2009). In 2010, the BMWi launched Gründerland Deutschland “Start-up Country Germany” www.existenzgruender.de website to educate and connect users to resources.
Sustainability policies	The Renewable Energies Act, the Energy Saving Ordinance, the Act on Heating Through Renewable Energy, the Amendment to the Act on Combined Heat and Power Generation, the Biogas Feed-In Ordinance, the Passenger Car Energy Consumption Labeling Ordinance, and the Amendment to the Heating Costs Ordinance all provide additional incentives (Pro INNO Europe 2009).
Regulatory compliance cost, time	The reform of the Limited Liability Company Act supports activities to reduce red tape (Second and Third Act to Reduce Bureaucratic Obstacles) (Pro INNO Europe 2009).
Intellectual property	The law on enhanced enforcement of intellectual property rights (IPR), as well as regulatory reforms shortens court proceedings on patent litigation and to introduce a period of prejudice preclusive to novelty (Pro INNO Europe 2009).
Investments in manufacturing, public-private partnerships	“High-Tech Strategy for Germany” supports new research programs, to fund innovations, and state-of-the-art technologies to bring to market maturity (Rammer 2007). The Leading-Edge Cluster Competition, part of the High Tech Strategy for Germany referenced above; funds clusters in emerging technology areas designated through competitive funding. “KMU-innovativ” simplifies SME access to funds, including simplified credit risk assessment.
Bank and economic policies	AIFM Directive imposes regulations on managers of alternative investment funds. Some worry about a protectionist effect (Baker, 2011). New banking regulations (Basel II) enacted in 2010 to change capital laws (Squire Sanders 2010).
Tax policy	The business tax reform 2008 contained a number of changes that should improve the internal financing of companies, particularly by reducing the corporate tax burden (Pro INNO Europe 2009).
Intensity of competition	Initiatives to increase competition on product markets currently focus on gas and electricity, postal services, public transport, and telecommunication (Pro INNO Europe 2009).

Japan

Manufacturing Innovation Structure

The coordination of manufacturing innovation in Japan is managed by a cabinet office called the Council for Science and Technology Policy (CSTP) under the Prime Minister. The CSTP oversees science and technology budgets and regularly reviews innovation-related policies. The Council on Economic and Fiscal Policy (CEFP) also regularly produces key innovation and economic policy outlines. The two most important ministries are the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and the Ministry of Economy, Trade and Industry (METI). METI creates subgroups formed around goals for technology development.

MEXT spends the majority of the science and technology budget, and it oversees partnering activities such as industrial cluster programs (including nuclear research in the Aomori Prefecture). METI has minor funding authority, but greater authority in industrial and trade policy (Ministry of Economy Trade and Industry 2010). Funding is outlined in the Third Science and Technology Basic Plan through FY2010.

Japan has strong auto, IT, electronics, robotics, and satellite industries. Table E-9 lists the primary industry sectors and areas of investments. The private sector is investing in technologies to counter unconventional threats to national security listed in the Council for Science and Technology Policy's Strategy for Innovative Technology (shown in bold in Table E-9).

Table E-9. Japan's current leading industry sectors and areas of investment.

Current leading industry sectors	Areas of investment
• Motor vehicles • Electronic equipment • Machine tools • Steel and nonferrous metals • Ships • Chemicals • Textiles • Processed foods	• Improvement in food security • Alternatives to rare-earth elements • Satellite technologies • Faster Observation and Ocean Exploration System • X-ray free-electron laser • Fast breeder reactor cycle technology • Next-generation super computer • Space transportation system

Source: Current leading industry sectors ranks the country's top industries by value of annual output from the Central Intelligence Agency (CIA 2011). Areas of investment reflect government spending as reported by the National Research Council (2010).

Japan has a strong innovation system but sluggish growth. Japan's innovation strategy concentrates on "push" funding strategies, rather than "pull" strategies. Japan funds a portfolio of research that is targeted to specific threats such as material shortages and food security, with short-term (5-year) plans (NRC 2010). Japan's portfolio is not

typically holistic or systems-based. For example, although the IT industry is strong, software is imported.

Japan's energy portfolios have shifted to investments in a system of technologies, such as funding multiple components needed to reach its goal for rooftop solar (Bleviss 2010). Government spending on overall R&D as a percentage of GDP is the largest among OECD member countries (OECD 2010c).

Innovation Strengths and Weaknesses

Japan's strengths are the quality of workforce and education, political stability, solid infrastructure, strong intellectual property, and concentration of world-class manufacturers with leading-edge know-how and quality control. It also has much higher investment in R&D as a percentage of GDP than the OECD average (OECD 2009b). The Ernst and Young survey found that investors want lower taxes, reduced labor costs, and better measures to reduce language barriers (Ernst & Young 2008).

Japan has strong intellectual property rights and a unique business structure. Called the keiretsu, the structure involves at least one major bank/trading company and a variety of industries, which can ensure more ready financing and protect supplier networks, though this structure is used less today (Bleviss 2010). Japan strengthened its academic intellectual property rights, decreased royalty cost for government-held patents, and started METI and MEXT programs to increase industry-academic partnerships. Japan is increasing the number of competitive grants and flexibility to allow multi-use funds, funding of joint industry research, and multiyear funds (European Union 2011).

In contrast to China's strategy to secure multiple geographic sources of rare materials, Japan is responding to similar material shortages by creating alternative technologies that do not use rare materials and securing resources abroad, potentially including North Korea (National Academies of Science 2010; Pro INNO Europe 2009). To minimize energy shortages, Japan has also become the most energy-efficient country in the world.

Japanese manufacturing competitiveness is expected to drop (Deloitte Council on Competitiveness 2010). Japan has been less successful in addressing workforce challenges. It has a high-quality workforce, but it is shrinking due to aging. Japan has not changed policy or cultural sentiment against immigration. Consideration is being given to removing tax laws, which would allow women to enter the workforce. Industry partnerships are more prevalent than academic partnerships, and Japan has experienced low start-up rates and low foreign direct investment. Japan has goals to double its foreign direct investment, in part to help with unemployment in certain sectors (European Union 2011).

Table E-10 provides examples of policies in key innovative strategies.

Table E-10. Selection of recent Japanese policies within innovation categories.

Key challenges as identified by reports	Examples of policies that address challenges
Labor force quality, number	Global Centers of Excellence Program (http://www.jsps.go.jp/english/e-globalcoe/), which provides funding support for establishing world-class education and research centers in university graduate schools and related research institutes (OECD 2008). World Premier International Research Centre Initiative, which aims to create globally visible research centers that attract top level researchers from around the world (OECD 2010b). Fellowships for overseas researchers operated by the Japan Society for the Promotion of Science and the extension of the visa stay in Japan from 3 years to 5 years. Some efforts have introduced wider information on research employment opportunities in Japan by the Japan Science and Technology Agency. The expansion of bilateral agreements with other countries is also seen as a further priority (CSTP 2007) (European Union 2011). 2009 government mentioned that it plans to introduce a new plan to increase the attractiveness of Japan for foreign researchers—no details have been forthcoming (CSTP 2009) (European Union 2011).
Access to capital	Small and Medium Enterprises and Regional Innovation Japan and National Life Finance Corporation (Pro INNO Europe 2009).
General resources	Measures for “investing in the future” include specific measures for solar-power generation, fuel-efficient vehicles and transport, and recycling products with valuable properties. It also includes the introduction of the Eco Points system for the purchase of environmentally friendly products (Pro INNO Europe 2009). Measures for “investing in the future” include developing “urban mines” and pursuing a strategy for securing stakes in natural resources abroad (Pro INNO Europe 2009).
Intellectual property	1999 Law on the Special Measures for Revitalizing Industrial Activities (NRC 2010). Reduced royalty for government-held patents (Pro INNO Europe 2009).
Public-private partnerships	Regional cluster policies promoted by government ministries, such as the Industrial Cluster Initiative, Knowledge Cluster Initiative, and City Area Program (European Union 2011). Universities have also been encouraged to develop Venture Business Laboratories to help foster start-ups likely to exploit university research (European Union 2011). The New Energy and Industrial Technology Development Organization provides a number of fellowships for staffing technology-transfer bodies (European Union 2011).
Tax policy	Proportional research and development (R&D) tax credit introduced by the Ministry of Finance for 8% and then 12% for R&D activities for Small and Medium Sized Enterprises (European Union 2011). Relaxed requirements for qualified ventures, rationalized verification procedures (European Union 2011). Tax credit for education and training costs if the ratio of cost to total labor cost exceeds 0.15% (European Union 2011).
Low foreign direct investment	Ministry goal to double foreign direct investment (U.S. Department of State 2009). New Japan External Trade Organization. JETRO has “reinvented” its organization from an export-promotion agency to an economic-development organization that is seeking to attract Foreign Direct Investment (European Union 2011).

The Republic of South Korea

Manufacturing Innovation Structure

The Republic of South Korea's governance structure has recently undergone change. Research and development (R&D) programs are divided among governmental ministries, which have different R&D policy missions and goals. The National Science and Technology Council (NSTC) sets the direction of funding and coordinates the research budget through committees, chaired by the president with ministers and private-sector members represented (including a committee on key industrial technologies).

Two ministries control innovation policies and funding: (1) the Ministry of Knowledge Economy oversees economic policy, including the Small and Medium Business Administration and the Korean Intellectual Property Office, and (2) the Ministry of Education, Science and Technology (MEST), which was founded in 2008 by merging previous ministries, controls mostly basic research and directs science and technology policy.

Three research councils report to the prime minister to coordinate funds specifically for government-funded research institutes performing research, including the Korea Research Council for Industrial Technology. The president also has an expert advisory group, the Presidential Advisory Council on Science & Technology (PACST). Finally, ministries use two main nonprofits to aid in policy planning and evaluation, the Korea Institute of Science and Technology Evaluation and Planning (KISTEP) and the Science and Technology Policy Institute (STEPI) (European Union 2011).

South Korea is shifting away from having a catch-up model of innovation by acquiring advanced technologies from abroad rather than a broader strengthening of its knowledge base (Baek and Jones 2005). It is also seeking to move from the historical focus of innovation through *chaebol*, the large conglomerate Korea houses, to use more demand-side policies (OECD 2009b).

Engineering is the most funded field, with the greatest number of graduates in electronic engineering. Development is the most funded stage of research, with basic research funding relatively low (European Union 2011).

Future investment goals are stated in “VISION 2025: Development of Science and Technology” and “Science and Technology Basic Plan” of the Lee Myung Bak Administration (also known as “the 577 Initiatives”). The 577 Initiatives identified seven major technology areas to concentrate on, including nuclear and fusion power. It also identifies “key industrial technologies” and includes policies to develop a private-led innovation system and support for regional innovation systems.

Table E-11 lists primary industry sectors and areas of investment.

Table E-11. South Korea's current leading industry sectors and areas of investment.

Current leading industry sectors	Areas of investment
• Electronics • Telecommunications • Automobile production • Chemicals • Shipbuilding • Steel	• Global-issues-related technologies: automobile, shipbuilding, machinery and manufacturing process, semiconductor, displays. • State-led technologies: satellite, next-generation weapon, next-generation nuclear reactor technology, etc. Level of core military technologies (in comparison to advanced countries, 80% by 2012). • "Green ocean" emerging industrial technologies: s IT and health technologies. • Knowledge-based service technologies: advanced logistics, converging technology of communication and broadcasting, etc. • National-issues-related technologies: disease, food, IT nanodevice technology: Climate change, energy • Basic and convergent technologies: biochip and biosensor, intelligent robot, nano-based convergent/composite-materials technologies, etc.

Source: Current leading industry sectors ranks the country's top industries by value of annual output Central Intelligence (CIA 2011). Areas of investment reflect a selection of fifty technologies listed by (UK Ministry of Education Science and Technology).

South Korea has a significant defense-research concern because of its geographic location. The country recently signed the India-South Korea Defense Agreement, which identifies futuristic defense technology areas for co-development (with joint intellectual property) and co-production of defense products with India's industry. The priority areas are marine systems, electronics, and intelligent systems (*India South Korea Defense Cooperation* 2010). One researcher described Korea's focus on security R&D is to achieve greater autonomy through its improved economic and military capabilities, and subsequent changes in the U.S.-South Korea alliance (Rask 2011).

Innovation Strengths and Weaknesses

South Korea has emerged as the world's largest shipbuilding nation. It ranks first in terms of semiconductors and displays and third in manufacturing competitiveness (Deloitte Council on Competitiveness, 2010 #219). South Korea has one of the highest rates of spending on R&D in the world, with strong investment from private firms, and it has succeeded in supporting growth from small and medium enterprises (SMEs) (OECD 2010a). It plans to build a "Science-Business Belt," constructing large-scale institutes for basic science and science parks (European Union 2011). Competition law and policy are considered relatively strong, and the percentage of S&T graduates is high relative to

OECD countries (OECD 2010c). However, foreign direct investment is low in South Korea, and the barriers to starting a new business are high in terms of cost and number of steps relative to OECD countries (OECD 2010a).

South Korea has an aging population and low fertility rates. Most workers retire around age 55, with a high share of non-regular workers (about 1/3) that often lack social insurance. The country depends on imported raw materials and energy (OECD 2010a). Linkages across business, university, and government research institutes are weak. The private sector almost exclusively relies on its own research, rather than licensing from government-funded research institutes or universities. Universities play a minor role in R&D, interaction with foreign researchers is limited, and development of the venture business sector remains weak (Baek and Jones 2005).

The World Trade Organization states that South Korea's low foreign direct investment is a result of burdensome regulations and the increasing cost of doing business there. Suggested solutions include improving the investment climate, addressing labor market rigidities, and addressing the likely decline in the labor force owing to a rapidly aging population (World Trade Organization 2006). The Capital Markets Consolidation Act of 2009 governs capital markets and investment services to allow firms to provide a broader range of services (OECD 2010a). The Korean government also operates several Free Economic Zones (FEZs) and has provided a range of investment incentives, including tax breaks, tariff-free importation, relaxed labor rules, and improved living conditions (Office of U.S. Trade Representative).

Table E-12 provides examples of policies in key innovative strategies.

Table E-12. Selection of recent South Korean policies within innovation categories.

Key challenges as identified by reports	Examples of policies that address challenges
Quality and availability of scientists, researchers, and engineers	"HRD (Human Resource Development) Collaboration for S&T Personnel Program": The Ministry of Education, Science, and Technology (MEST) implements the industry-demand-oriented HRD policies, such as Brain Korea 21 (program to support post-graduate programs at universities), and the NURI program (focused upon the teaching specializations and innovative capabilities of regional universities, worth €63 million in 2008) (European Union 2011). There is a plan to corporatize (privatize) national universities. Requirements for school quality have been increased (European Union 2011).
Infrastructure	Development of techno-parks (Ministry of Commerce, Industry and Energy). Development of venture towns (OECD 2009c).
Access to capital	Stimulate the development of private venture capital by initiating venture capital through a government fund—MOST Fund I & II, IT Investment Club(OECD 2009c).

Key challenges as identified by reports	Examples of policies that address challenges
Government investment in supporting public-private partnerships	"Special Venture Act" in 1998 and "Fostering Industrial Education and Industry-University Cooperation" in 2003. The purpose of these new laws was to help university professors to create venture firms and universities to set up industrial cooperation offices (European Union 2011). Ministry of Education, Science, and Technology (MEST) linkage programs; National Research Council, Engineering Research Council (€524 million); and NRDC (€322 million) in 2006 (European Union 2011). Ministry of Knowledge Economy (MKE) provided Technological Development Program for Industrial Innovation and Regional Technology Innovation. Small and Medium Business Administration (SMBA) provided Collaborative Technology Development for Industry-Academia-Research Linkage (€433 million). These programs promote the collaborative technological development through Industry-Academia-Research Linkage (European Union 2011).
Investments in science, technology, and innovation	Basic Research Promotion Plan will increase basic research funding, following governmental prioritization of projects (OECD 2009c). 2004 Implementation Plan for the National Innovation System, a plan to move from a catch-up to a creative innovation system (OECD 2009c).
Tax policy	Tax incentives for human resources, such as the income-tax deductions for researchers, the special tax treatments for foreign human resources, the income-tax exemptions for research expenses, and the temporary tax exemption for HRST foreign dispatch (European Union 2011). Corporate-tax deduction of 50% of the increase in R&D and HRD investments over the annual average investments of the past 4 years or 5% of the current expenditures for the same purposes (15% for SMEs). Corporate tax deduction of 5% of the total investment in equipment and facilities for R&D and/or HRD (European Union 2011).
Bank and economic policy	Stimulate the development of private venture capital by initiating venture capital through a government fund (OECD 2009c).
Quality control	Korean industrial standards have doubled over the last 5 years; work is underway to harmonize Korean standards to international standards (including those on new technology products) and for cooperation in global-standardization activities (World Trade Organization 2006).
Low foreign direct investment	The "Global Research Network" (7.8 billion KRW, or approx. €5.2 million) project and the 'Global Research Lab' (15.7 billion KRW, or approx. €10.5 million) project will facilitate joint research and interaction between Korean and foreign researchers (European Union 2011). Korean National Assembly passed the Financial Investment Services and Capital Market Act (NRC), effective 2009. It categorizes investment activities, then streamlines relevant permits and licenses.
Health of economic and financial system	Promotion of capital market for new start-ups: the development of the KOSDAQ, a second stock market for new start-up businesses (OECD 2009c). The Capital Markets Consolidation Act of 2009 governs capital markets and investment services to allow firms to provide a broader range of services (Hansakul 2008).

United Kingdom

Manufacturing Innovation Structure

With some exceptions, the UK Department for Business, Innovation and Skills (BIS) has primary authority over Scotland, Northern Ireland, and Wales. The Department

for Innovation, Universities and Skills (DIUS) is the major funder for the public sector, which receives the majority of direct funding. Other departments have research portfolios as well (Food, Defense, Rural Affairs, and Health). The Department for Business, Enterprise, and Regulatory Reform (DBERR) is jointly responsible for trade policy, trade promotion, and inward investment, taking on the previous Department of Trade and Industry programs. Funding to the public sector is mostly through block grants awarded by Research Councils to Universities. The new Research Excellence Framework is updating the selection criteria for grants.

The UK innovation system is moving away from innovation policy, which relies on direct funding and thematic science sectors, toward one that builds the conditions and framework for innovation. BIS outlines the general economic policy for competitiveness in the “Plan for Growth” (UK HM Treasury 2011). The United Kingdom recently began an Annual Innovation Report and webpage gathering innovation analysis and will create an Innovation Research Centre to inform the policy community (UK Department for Innovation 2008). According to experts,⁶ the country’s goals include the following (Anonymous 2 on Semiconductors 2011):

- Demanding innovation, which includes promoting procurement strategies and lowering regulatory barriers.
- Supporting business innovation, which includes implanting policies for technology transfer, supporting smaller businesses, and supporting commercialization from academia.
- A strong and innovative research base, which includes intellectual-property support and new research and evaluation measures for innovation.
- International innovation, which includes participating in the global market.
- Innovative people, which includes business knowledge exchange and sector-based skills education.

The United Kingdom has a strong manufacturing industry, with slow growth. It is expected to fall from 17th to 20th place in manufacturing competitiveness in the next 5 years (Deloitte Council on Competitiveness 2010). The United Kingdom makes use of “demand side” or “pull” strategies for innovation. The United Kingdom’s aerospace and pharmaceutical industries in particular are among the strongest in the world, and they have a few R&D-intensive sectors such as motor vehicles, information technology, and electronics (OECD 2010c). Patents show a clear specialization of UK research in health, environment, and biotechnology (especially pharmaceuticals and nanotechnologies) (OECD 2010c).

⁶ These experts preferred to remain anonymous.

Table E-13 lists primary industry sectors and areas of investment in the United Kingdom.

Table E-13. United Kingdom’s current leading industry sectors and areas of investment.

Current leading industry sectors	Areas of investment
• Machine tools • Electric power equipment • Automation equipment, railroad equipment, shipbuilding, aircraft, motor vehicles and parts • Electronics and communications equipment • Metals, coal, petroleum, paper, and paper products • Chemicals • Food processing, textiles, clothing • Other consumer goods	• Research Council Energy Program • Living with environmental change • Global uncertainties: security for all in a changing world (security) • Lifelong health and wellbeing • Nanoscience • Digital economy • High-value manufacturing: step change in competitiveness; value systems • Photonics: Photonics21—next-generation optical Internet access • Materials: sustainable materials and products • Energy generation and supply • Energy generation and supply: fuel cells and hydrogen technologies • Creative industries: content in a digitally networked world • Intelligent transport systems and services: informed personal travel • Network security: interdependency, risk and complexity

Source: Current leading industry sectors ranks the country’s top industries by value of annual output Central Intelligence (CIA 2011). Areas of investment reflect government spending as reported by (UK Department for Business Innovation and Skills 2008).

The UK planning document for the defense industry is the 2005 “Defense Industrial Strategy” (Defense White Paper), as well as the “Technology Strategy” and the “National Defense Industry Technology Strategy.” The United Kingdom considers the United States an important defense industry partner. The UK market for defense equipment and services is the second largest in the world. The United Kingdom has specific strategies to align defense research with industry, and the Ministry of Defense is moving away from conducting in-house research to providing grants for up to 60% of its budget.

The Ministry of Defense sets priorities, both published and communicated directly to industry, through “Supplier Day” presentations, and it jointly funds Defense Technology Centers (DTCs) in Data and Information Fusion, Human Factors Integration, Electromagnetic Remote Sensing, and Systems Engineering for Autonomous Systems (Ministry of Defense 2005). The country’s technology priorities are broad and include emerging technologies in defense (see Table E-14).

Table E-14. United Kingdom's current defense technologies and areas of investment.

Current defense technology priority areas	Technologies with emerging defense relevance
• Secure and robust communication technologies • Data and information technologies • Sensor technologies • Guidance and control technologies • Electronic combat technologies • Integrated survivability • Automated information and knowledge technologies • Technologies for remote and autonomous operation • Power source and supply technologies • Human performance • Technologies to support system integration and support	• Smart materials and structures • Microelectromechanical systems (MEMS) • Novel energetic materials, enhanced properties • Supersonic and hypersonic technologies • Biotechnology and its effect on human performance • Wideband, high-power electronics • Quantum-state systems for computing and communications • Nanotechnology

Source: Ministry of Defense (2005)

Innovation Strengths and Weaknesses

R&D as a percentage of GDP in the United Kingdom is slightly below the OECD average. The country has difficulty translating knowledge into “new to market products” and intellectual capital (referred to elsewhere as the flow of knowledge between the science base and industry). Although tertiary graduation rates are high, basic and intermediate skill levels are weaker (Pro INNO Europe 2009). The proportion of R&D personnel is also low compared with other European Union Member States (European Union 2011). While the education system is strong, student entrance in fields such as physics and chemistry is low, and less than half the UK graduates in engineering and physical sciences go on to pursue careers in science (European Union 2011).

The United Kingdom is encouraging business investment and linkages through its “Supporting business innovation” goal. The United Kingdom has a strong equity market, but has put policies in place to increase support for small and medium enterprises (SMEs).⁷ It also has policies in place to create a stronger technology-transfer linkage between academia and industry and strong private investment in research.

The United Kingdom introduced an “Innovation Nation Plan” in 2008 that focuses on demand-side policies, some of which are reflected in its “Demanding Innovation” goal. The “Innovation Procurement Plan” introduced in 2009 requires procurement plans for governments, large facilities, and capital programs. The United Kingdom also began a Small Business Research Initiative to designate a portion of the government budget for

⁷ A fact sheet on access to financing capital is available at <http://www.bis.gov.uk/assets/biscore/enterprise/docs/s/10-1375-smes-access-to-finance-faqs.pdf>.

competitive R&D contracts for SMEs, with major contracts awarded in defense, health, and construction. The United Kingdom attributed part of its high productivity to a robust standards system in industry. Biometrics, nanotechnology, and regenerative medicine are identified as the next targets for standards development (OECD 2011b).

Table E-15 provides examples of policies in key innovative challenges.

Table E-15. Selection of recent United Kingdom policies within innovation categories.

Key challenges as identified by reports	Examples of policies that address challenges
Quality and availability of scientists, researchers, and engineers	Funding to universities for the provision of 2 weeks of transferable skills training per year for Ph.D. and post-doctoral students to meet the needs of industry (European Union 2011). Provide support for very high cost and “vulnerable” science subjects, that is, areas that are strategically important to the economy and society but with relatively low student demand (European Union 2011). “The Plan for Growth” includes expansion of the University Technical Colleges program to establish 24 colleges by 2014 (UK HM Treasury 2011). Increase funding for the Train to Gain vocational training to employed individuals; establishment of a UK Commission for Employment and Skills; a Skills Funding Agency (operational from 2010); and an integrated employment and skills system (European Union 2011). Support for additional employer-led National Skills Academies, which includes manufacturing, nuclear, process, and environmental technologies; IT; and materials academies (National Skills Academy 2008).
Access to capital ^a	The 2009 Innovation Investment Fund is a “fund of funds” to support specialist Technology Funds to invest in high-technology SMEs, start-ups, and spin-outs with high potential of growth and innovation. The SME scheme was extended to companies with up to 500 employees (European Union 2011). Risk capital for research and development (R&D), either on a regional basis (e.g., the Regional Venture Capital Funds) or via national schemes such as the Enterprise Capital Funds, Selective Finance for Investment in England, and Enterprise Capital Funds (European Union 2011). Enterprise Finance Guarantee, Community Investment Tax Relief (Pro INNO Europe 2009).
Tax policy	Tax Credits schemes together represent the largest innovation support measure. In 2002, extended SME R&D tax credit to large companies (European Union 2011). The Government aims to create the most competitive corporate tax system in the G20 (the Group of Twenty Finance Ministers and Central Bank Governors) and it took immediate action in its plans for reducing Corporation Tax. From 2011: small profits rate will be reduced from 21% to 20%; the main rate of corporation tax will reduce from 28% to 27%; followed by year-on-year reductions to 24% in 2015.

Key challenges as identified by reports	Examples of policies that address challenges
Linkages, public-private partnership policies	R&D programs without thematic focus include The Higher Education Innovation Fund, Knowledge Transfer Partnerships, CASE, Faraday Partnerships (European Union 2011). “Single pot” funding of the Regional Development Agencies. The RDAs are in charge of implementing clusters policy in each of the nine English regions (European Union 2011). Innovation Platforms are forums for government and industry to plan action. Two initiatives from them are in Network Security and Intelligent Transport Systems and Services (Economic and Social Research Council 2006b, 2006a). The Technology Strategy Board has plans with 18 government sponsors of Knowledge Transfer Partnerships (KTPs). In addition, a shorter KTP scheme is to be introduced to facilitate shorter, light touch collaboration (UK Department for Business Innovation and Skills 2008)
Connections between actors	The Technology Strategy Board requested the adoption of an Innovation Procurement Plan from every Government department, placing innovation at the center of every policy area (European Union 2011).
Intellectual property	UKTI export and Business Link advisors will receive training from the UK Intellectual Property Office (IPO) in advising businesses on IP management. UK IPO will provide online support to help small businesses exploit their IP and will continue to develop the Lambert online toolkit of model university-business licensing agreements, which cuts the cost and complexity of IP transactions (UK Department for Business Innovation and Skills 2008)
Supply chain	Accelerated launch of the new reformed Manufacturing Advisory Service from January 2012 with an additional £7 million to deliver supply-chain activities over the next 3 years (UK HM Treasury 2011).
Demand	Each government department will include an Innovation Procurement Plan as part of its Commercial Strategy, setting out how it will drive innovation through procurement and use innovative procurement practices (UK Department for Business Innovation and Skills 2008).

^a A fact sheet on access to financing capital is available at: <http://www.bis.gov.uk/assets/biscore/enterprise/docs/s/10-1375-smes-access-to-finance-faqs.pdf>.

Appendix F.

Semiconductor Manufacturing

Introduction

Today's information processing needs are powered by silicon-based integrated circuits (ICs). ICs (or microprocessors) were first developed in the 1950s, when the U.S. aerospace industry needed sophisticated electronics that could be installed on rockets to provide onboard guidance. As a result, there was a tremendous emphasis on the packing density of electronic functions that could reduce the size and weight of satellite and missile systems. Integrated circuits have grown steadily in complexity since the “planar process” for connecting individual transistors on a common silicon platform was developed in 1958. The silicon microprocessor today—containing more than two billion transistors, each functioning, interconnected by a well-defined, hierarchical wiring scheme, and measuring in nanometers—is one of the more complex pieces of machinery ever manufactured.

This rate of increase in complexity, which is unique to the semiconductor industry, has been achieved by scaling down circuit components with each successive technology generation (approximately every 2 years), thereby doubling the number of transistors that can be placed in an integrated circuit at constant cost. First proposed by Intel co-founder Gordon Moore in 1971, this characteristic is referred to as Moore's law. Scaling down transistors devices also improves their performance and power, resulting in a constant doubling of computing performance at near constant cost every 2 years (Dennard et al. 1999).¹ This phenomenon has led to the explosive growth of the semiconductor industry in the last 40 years, fueling the growth of the information and communication technology (ICT) industry and providing solutions for business, defense, consumer, and societal needs.

Rationale for Selection Based on Criteria

Microelectronics is a platform technology for all computing and information processing needs today; the ICT sector contributes over \$6 trillion to the global economy. According to MIT economist Dale Jorgenson, from 1995 to 2005, information-technology (IT)-producing and intensive-IT-using industries have accounted for 50% of

¹ Known as Dennard's scaling rules, if the transistor's lithographic dimensions and the operating voltage are scaled down by the same factor, the resulting device is faster, less expensive, and more power efficient.

economic growth while making up only 3% of the GDP (Jorgenson 2005). Furthermore, the next two decades will see increasing influx of microelectronics in other sectors from interconnected computing environments to intelligent sensing and interactive systems in spaces such as bio-electronics, energy grid systems and transportation systems (Herr 2011; Jammy 2011).

Semiconductor manufacturing is one of the most advanced manufacturing processes today, involving controlled, repeatable and virtually error-free fabrication of structures at the atomic scale. The global investment in semiconductor manufacturing is high and continually increasing. In 2011, fabrication facilities worldwide spent over \$44 billion (iSuppli 2011) in equipment and increasing capacity.

The U.S. defense enterprise is critically dependent on the sophistication of its electronic systems. The gradual off-shoring of IC manufacturing (including defense-critical systems) to Southeast Asia over the past 20 years has enabled these regions to become competitive with the United States in IC manufacturing. *China's rapid rise in IC technology and manufacturing and its rapid progress toward an indigenous industry is cause for concern* (Price Waterhouse Cooper 2010).

Present-Day Status of the Semiconductor Industry

Semiconductor manufacturing today is a mature, global industry with \$300 billion in revenue and manufacturing facilities in over 20 countries. It is the cornerstone of a global IT economy, supporting a \$2 trillion market in electronic products and an estimated \$6 trillion in service industries across sectors ranging from health care and transportation to banking and defense (Zhang and van Roosmalen 2009).

The dominant manufacturing process used for digital electronics today is called the complementary metal oxide semiconductor (CMOS) process. The process involves more than 300 sequential steps, some of them involving patterning nanometer-length features onto silicon, using high-precision, high-volume equipment. As design and process technologies matured, the industry progressed from being vertically integrated toward a more horizontal structure. In 1980, Carver and Conway established the rules for modern integrated circuit design, leading to a decoupling of product design and manufacturing.² *Now, with the establishment of manufacturing-independent design rules for integrated circuits, IC designers no longer needed to be co-located with the manufacturing side of the business.* This decoupling led to the creation of the electronic design automation industry.

² In 1980 Carver Mead and Lynn Conway wrote *Introduction to VLSI Systems*. This landmark text developed and standardized very-large-scale integration (VLSI) system design for the first time, making the knowledge available to a much larger audience, ultimately resulting in the separation of design from production/manufacturing and establishing electronic design automation as its own discipline.

The costs of both R&D and manufacturing in the semiconductor industry have risen steeply with each new technology generation (from \$100 million in 1985 to \$5 billion in 2010) (Mims 2010). Combined with the vertical disintegration of design and manufacturing activities, this cost increase has resulted in two significant trends over the past two decades. First, U.S. semiconductor companies have off-shored significant portions of their operations to contract manufacturers who are concentrated in Southeast Asia, where substantial investments by local governments has helped the growth of manufacturing “foundries.” Second, rising costs have led to increasing consolidation within the industry and the loss of a competitive supplier base, particularly in the United States.

Starting in 1985 with Taiwan, where former Texas Instruments executive Morris Chang started the Taiwan Semiconductor Manufacturing Company (TSMC) (Perry 2011) with the backing of the Taiwanese government, the semiconductor manufacturing ecosystem today has mostly bifurcated into fabrication-less (fabless) companies, which design their products but outsource the manufacturing to a third party, and foundries, companies that provide a noncompetitive manufacturing facility for fabless companies. The few manufacturers who design and manufacture their own products in house, such as Intel Corp, are called integrated device manufacturers (IDMs).

Today, Japan, Taiwan and Korea have an established position in the industry, with China slowly ramping up its foundry capabilities. While U.S. companies Intel and AMD have led the microprocessor market, Japan has historically led in memory products. In recent years, however, Korea (Samsung) has taken the lead in memory products, as well as the mobile devices industry. China is coming up very fast, aided by government policies to attract foreign manufacturers to set up foundries in the country. Its semiconductor industry accounted for 11% of the global industry in 2009, up from 2% in 2000 (Chitkara 2010). The growth of manufacturing activity in this region has slowly eclipsed that of Europe and the Americas.

Figure F-1 shows the top-20 sales leaders in the semiconductors market for 2010. Of the top-five companies, TSMC is the only foundry. The top-20 manufacturers control over 66% of the market, a direct result of increasing consolidation over the past 10 years.

1Q11 Rank	2010 Rank	Company	Headquarters	2010 Tot Semi
1	1	Intel	U.S.	40,154
2	2	Samsung	South Korea	32,455
3	5	Toshiba	Japan	13,028
4	3	TSMC*	Taiwan	13,307
5	4	TI	U.S.	13,037
6	6	Renesas	Japan	11,650
7	8	ST	Europe	10,346
8	7	Hynix	South Korea	10,432
9	9	Micron	U.S.	9,092
10	10	Qualcomm**	U.S.	7,204
11	11	Broadcom**	U.S.	6,589
12	12	AMD**	U.S.	6,494
13	14	Infineon	Europe	6,049
14	15	Sony	Japan	5,645
15	16	Freescale	U.S.	4,357
16	18	Fujitsu	Japan	4,147
17	13	Elpida	Japan	6,446
18	17	NXP	Europe	4,321
19	19	UMC*	Taiwan	3,965
20	23	Nvidia**	U.S.	3,575
Top 20 Total				212,293

*Foundry

Source: IC Insights (2011). (* Foundry, ** Fabless).

Figure F-1. Global ranking of semiconductor companies by sales.

Figure F-2 shows estimates of global semiconductor revenue in 2010 by geographic region of the company headquarters.

Preliminary Estimate of Global Semiconductor Revenue in 2010 by Company Headquarters Location
(Revenue in Millions of U.S. Dollars)

2009 Rank	2010 Rank	Company Headquarters	2009 Revenue	2010 Revenue	Percent Change	Percent of Total	Cummulative Percent
1	1	Americas	\$110,936	\$147,291	32.8%	48.5%	48.5%
3	2	Asia-Pacific	\$44,598	\$65,363	46.6%	21.5%	70.0%
2	3	Japan	\$49,857	\$63,766	27.9%	21.0%	90.9%
4	4	EMEA	\$24,115	\$27,586	14.4%	9.1%	100.0%
		Total	\$229,506	\$304,006	32.5%	100.0%	

Source: IC Insights (2011).

Note: EMEA (Europe, the Middle East, and Africa) is a regional designation used for government, marketing and business purposes.

Figure F-2. Semiconductor revenue by region.

This discussion of the microelectronics industry is confined to the digital CMOS IC (more commonly called the semiconductor chip), the dominant product of the commercial manufacturing enterprise. The semiconductor chip is based on the transistor,

a device used to switch and amplify electric signals and the fundamental building block of modern electronic devices. Currently, ICs in microprocessors pack more than a billion transistors onto a dime-sized substrate.

The industry is now reaching the basic physical limits to linear CMOS scaling. Scaling (reducing) the operating voltage causes an exponential increase in the “leakage” current (via direct quantum-mechanical tunneling) when the switch is turned off. This significantly degrades transistor functioning. To avoid this, manufacturers now scale down the device at *constant voltage* (approximately 1 V), which has effect of exponentially increasing the power emitted when the transistor operates at high speeds (Theis 2011; Theis and Solomon 2010; Haensch et al. 2006). With the heat generated by a processor already exceeding that of a hot plate, further reduction is not a viable option. The continued ability to achieve full benefits of scaling is thus diminishing as manufacturers are being forced to trade-off between transistor density and performance (speed) to avoid excessive increases in power density of the chip (Welser et al. 2010).

There is growing interest in technologies that would carry the industry past the scaling limitations. Industrial consortia such as U.S.-based Semiconductor Manufacturing Technology (SEMATECH) are exploring technologies to improve chip performance via increased system-level functionality, in what is called the system-on-chip concept (Jammy 2011). Others, such as the Japanese Nanoelectronics network and researchers at the U.S.-based Nanotechnology Research Institute, are actively engaged in the development of new devices (Cavin 2004; Bernstein et al. 2010)—new physics, new materials—that can function at much lower voltages and could allow continued miniaturization beyond the limits now imposed by the CMOS transistor. The next sections explore these emerging concepts in the microelectronics industry.

Emerging IT Applications that Will Drive Technology Development over the Next 20 Years

The semiconductor industry today is driven by wireless computing needs as the market for mobile devices has overtaken that of desktop computers. The future of semiconductor manufacturing will be increasingly driven by powerful mobile interconnected systems (Cisco Systems 2011), laying the groundwork for enhanced human-computer interaction and a ubiquitous sensor-driven world of intelligent environments (Rabaey 2011; Jammy 2011; Doering 2011; Rocco 2011).

In the short term, fast proliferating mobile systems and networks will necessitate secure handling and storage of vast amounts of personal information (Power 2011; Rabaey 2011). Cloud computing, which uses virtualization (an abstraction of services away from the servers themselves), will increasingly allow businesses and consumers to access reliable, scalable, and diverse services without incurring the cost of dedicated hardware (Fox 2010; Armburst et al. 2001). By optimizing the usage of large server

“farms,” the computing infrastructure can also be made more energy efficient (Nelson 2010). On another level, advances in biometrics, voice recognition, free-form display technologies, and location-based services will advance human-computer interactions (Jammy 2011).

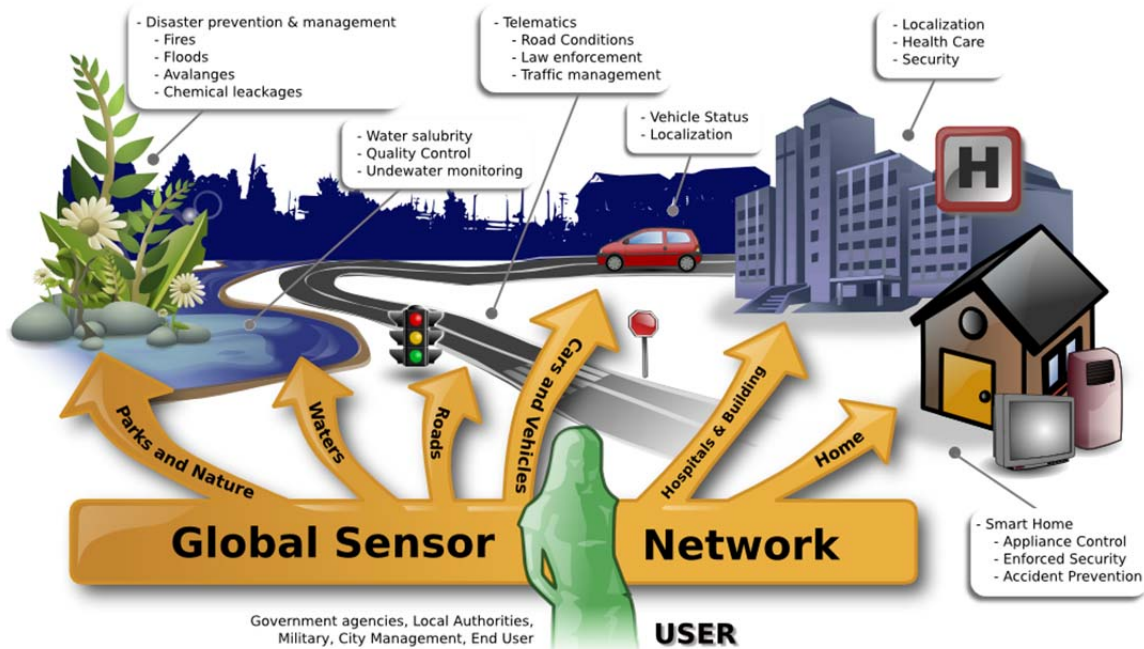
Computer chips will integrate more and more functionality, not only processing and storing information, but also integrating on-chip sensing and communication. As a result, they will find increasing application in new sectors, such as bio-electronics and other medical applications, intelligent (self-healing and fault tolerant) control of smart grids, and automated transportation systems (ITRS 2010b; Bonomi 2010).

The vision for a cyber-physical world combines the IT platform of today (mobile devices connected to the cloud) with networks of wireless sensors that make the computing platform ubiquitous (PCAST 2010a; Sha et al. 2009). The sensors—integrated circuits approaching molecular limits—may be embedded into objects or cover complete walls, leading to trillions of connected devices that collaborate in an intelligent and adaptable manner to fulfill common goals (Rabaey 2008).

In and of themselves, sensor networks have applications in energy, health care, defense industrial automation, smart cities, and more. Cyber-physical systems are created when these sensor networks are connected to the server cloud, with mobile-computing devices forming the middle layer. This concept, depicted in Figure F-3, is variously known as the “Internet of Things” and the “Swarm at the Edge of the Cloud.”

With the anticipation that wireless Internet usage will explode over the next decades, global research groups (Multi-scale Systems Research Center, part of the Semiconductor Research Corporation (SRC), and its participating universities in the United States; the European Research Cluster on the Internet of Things in the EU, among others) have been working on various pieces of puzzle. Turning this vision into reality will require powerful new devices with integrated sensing capability, faster networks, and a virtualized software environment (NITRD 2011; Rabaey 2011).

One of the earlier realizations of cyber-physical systems is likely to occur in enabling automated transportation (Markoff 2010), where an intra-automobile network interacts with an external, sensor-enabled network to process remote instructions (Zhang and Roosmalen 2009; Trew 2011; Bonomi 2010). These concepts also push advances in cyber-biological systems (Jovanov et al. 2005; June 2010), as well as hands-free computing or augmented reality systems, currently used primarily in the gaming industry (such as Nintendo’s Wii), but eventually anticipated to inform all human-computer interaction (Rabaey 2011).



Source: <http://www.srcf.ucam.org/~tsl26/technicalBlog/post2/>.

Figure F-3. Global sensor network.

The following sections will examine global trends in microelectronics technology development and manufacturing that will support the realization of these future applications, as well as larger factors (regulatory and socioeconomic among others) that continue to shape this industry.

Domains Explored for the Study

To obtain a landscape of the semiconductor manufacturing industry and its evolution in the 5-, 10-, and 20-year time frames, we focused on the entire breadth of the industry supply chain, but with special emphasis on the following:

- *Technology and manufacturing trends*, which include emerging device and process technologies that will drive the changes in the manufacturing process over the next 10 to 20 years. This includes research in new classes of materials that have the potential to enhance the functionality and performance of present-day microelectronics, new device and system concepts, new process technologies, and challenges in high-volume manufacturing.
- *Software tools* for design automation and modeling and simulation and their increasing impact in the future.
- *External factors* such as shifts in the global supply-chain, issues relating to intellectual-property protection and government regulations, education and workforce issues, and other factors that will shape the trajectory of this industry.

- *Global landscape* of microelectronics technology and manufacturing, including strengths and weaknesses of competitor countries, focusing on Japan, Korea, Taiwan, the EU, and China.

Dominant Trends in Technology and Manufacturing

Dominant trends in semiconductor technology over the next two decades will include the following:

- Low-power and low-energy systems (Jammy 2011), which will be needed as more devices (especially those with integrated sensors) have to integrate seamlessly with the environment.
- Increasing wireless capability and connectivity, particularly as cloud computing needs escalate (Jammy 2011; Rabaey 2011; Merzbacher 2011).
- Convergence of computation, storage, sensing, and communication functionality on the chip by integrating heterogeneous materials and components (Jammy 2011).
- Increasing use of nanoscale processes in device fabrication; slow but eventual transition from top-down to bottom-up manufacturing (Doering 2011; Herr 2011).
- Storage and management of increasing volumes of data while addressing integrity, safety, security, and privacy concerns (Rabaey 2011; Merzbacher 2011). While this is not a new issue, it has recently resurfaced due to various inexplicable large system failures, including the recent stock-market crash and recovery that occurred on August 8, 2011.³
- Influx of biologically based design, architecture, and concepts, ultimately aiming for massively parallel, fault-tolerant neuro-morphic systems (Likharev, 2011).

Cumulatively, these trends would enable advances in powerful and intelligent computing environments, as well as enhanced modes of human-computer interaction (Rabaey 2011).

Road-mapping the Semiconductor Industry

Technology planning and R&D in the semiconductor industry is a large-scale, long-term, and multi-billion dollar operation, which is largely collaborative. The Semiconductor Industry Association (SIA), in collaboration with international semiconductor technology associations, publishes roadmaps every other year to present an industry-wide consensus on the R&D needs of the industry on a 15-year horizon.

³ See <http://www.economist.com/blogs/dailychart/2011/08/us-stockmarket-declines-and-gdp>.

In 2010, the industry roadmap redefined the technological and manufacturing trajectories along the following complementary paths:

- *“More Moore”*—This category includes modifications in design and materials in the current manufacturing process to compensate for the limitations in linear scaling and extend the benefits of the CMOS process to the maximum possible extent (ITRS 2010a).
- *Functional diversification or “More-than-Moore” or “System-on-Chip”*—This methodology involves incorporating analog devices (such as sensors, actuators, RF devices, and passive components), which are typically integrated at the system board level, to be placed directly onto the chip (also called system-on-chip, or SoC) (ITRS 2010a). A compact system with heterogeneous functionality will drive the proliferation of integrated circuits in improved communications, bio-electronics, and transportation (Trew 2011).
- *Beyond CMOS*—This trajectory includes research on emerging devices and materials, focused on a “new switch,” which will initially supplement the functioning of the current CMOS and eventually supplant it.⁴ These devices and memories are anticipated to use new state variables (such as electron spin, magnetic spin, molecular state, etc.), which allow functional scaling substantially beyond that attainable by “scaled CMOS.”⁵ Examples include carbon-based nanoelectronics, spin-based devices, ferromagnetic logic, atomic switches, and nanoelectromechanical-system (NEMS) switches (ITRS 2010a; Chen 2011a; Welser 2011).

It should be emphasized that these technology developments are not sequential but occur in parallel, with advances in one feeding into another area. Each of these trajectories will require substantial changes in design, architectures, system integration models, and process technologies. The sections below discuss the forecasts on trends that are expected to cause significant changes, including a few disruptive ones in the industry.

Near-Term Technology Trends (“More Moore”)

Device and Materials

Continued scaling: Because continued scaling of transistor dimensions results in extreme heat dissipation at the limits of high performance, manufacturers now seek to improve chip performance using a combination of:

⁴ A “new switch” refers to information-processing technology that provides an alternative to the current mode of storing information states in the form of electric charge.

⁵ As defined in terms of functional density, increased performance, and reduced power consumption.

- Continued dimensional scaling, to the extent feasible and cost effective.
- “Equivalent scaling,” that is, changes in materials, design, and process that combine to give a performance improvement equivalent to scaling down the chip (e.g., introducing new materials such as high-K dielectrics in place of the traditional silicon dioxide insulator and using three-dimensional transistors such as the FinFET and the tri-gate transistor (Doering 2011; Welser 2011).
- Design-equivalent scaling, that is, new design methodologies such as the use of multi-core architectures, general-purpose graphical processor units (GPGPUs), and different modes of low-power design to drive improved performance (Theis 2011; Doering 2011). All these methods utilize the parallel-instruction capability of multi-core processors to achieve speed-ups.

In the areas of memory and storage, research has focused on unifying hard-disk memory and chip-based memory into a single unifying non-volatile memory⁶. Technologies such as the phase-change memory,⁷ ferroelectric RAM (FeRAM),⁸ and magnetoresistive random access memory (MRAM)⁹ are under development as potential replacements for the universal flash memory (Anonymous 2 on Semiconductors 2011).

Materials: Several materials are being researched and characterized for their potential insertion into CMOS devices (replacing the channel) to improve performance, as well as form the basis of new “beyond CMOS devices.” The materials attracting the most attention are graphene (Welser 2011; Chen 2011a; Trew 2011), carbon nanotubes, and compound semiconductor nanowires. However, since the silicon-based CMOS process has been a technological juggernaut for the past four decades, there is an enormous resistance to the integration of new and old materials—including compound semiconductor materials and germanium—because they are not compatible with the existing manufacturing process (Herr 2011).

Integration: Another trend that is gaining momentum is three-dimensional integration of circuits (Lu, Rose, and Vitkavage 2007), in which two or more layers of active electronic components are vertically integrated into a single circuit. This is made possible by three-dimensional interconnect technologies using through-silicon vias

⁶ Volatile memory is memory that loses its contents when the computer loses power. Random access memory (RAM) is the most common form of this form of storage. Non-volatile memory retains stored information even when the computer is powered down.

⁷ A phase-change memory technology uses the unique property of chalcogenide glass to store information. Heat generated by the passage of electric current causes the material to switch between crystalline and amorphous states.

⁸ FeRAM technology uses the property of spontaneous and reversible polarization under electric fields to store information.

⁹ MRAM technologies use the magnetic properties of the material to store charge.

(TSVs), which will dramatically reduce interconnect length and therefore transmission delays. Three-dimensional integration for stacking memory and logic components provides a higher memory density at lower power for mobile applications (Gu 2008). This concept of moving system integration to the third dimension has been called “the largest shift of the semiconductor industry ever, one that will dwarf the PC and even consumer electronics eras” (Siblerud 2009).

Transmission: Silicon photonics are being developed to enable integration of optical transmission systems onto the chip, overcoming the constraints of today’s copper interconnects (Theis 2010). This would result in faster and more energy-efficient chips than are possible using conventional technologies. While silicon photonics circuits have recently been demonstrated and are a few years away from commercial production, Intel leads the pre-commercialization development in integrated silicon photonics (Theis 2011).

Manufacturing Process

Lithographic patterning, critical for defining lateral dimensions on the chip and translating design into product, is a big challenge in the next decade (Doering 2011). There is currently a pressing need for next-generation lithography (NGL) technologies for nanoscale printing, and leading equipment manufacturers Nikon (Japan) and ASML (Holland) are in a close race to bring future lithography techniques such as extreme ultraviolet (EUV) lithography to market (Doering 2011).

As emerging devices scale down to nanometer and sub-nanometer levels, robust and efficient methods for atomically precise placement and solutions for intelligent fault tolerance become essential (Pillai 2011; Jammy 2011; Doering 2011). On the factory-floor scale, globally distributed production systems need to become increasingly scalable, flexible, and extendable (Pillai 2011). Improving all these characteristics is essential for improving process control. Further, as manufacturing systems are increasingly automated and subject to remote control, information security and cyber-security become essential (Pillai 2011).

Medium-Term Technology Trends (“More-than-Moore” or “System-on-Chip”)

The United States leads in these technologies, but Korea and Taiwan are highly competitive.

Device and Materials

“More-than-Moore” or “System-on-Chip” is the idea of integrating heterogeneous components onto the silicon platform to increase the functionality of the chip itself (ITRS 2010b). Figure F-1 summarizes this integration of functionality.

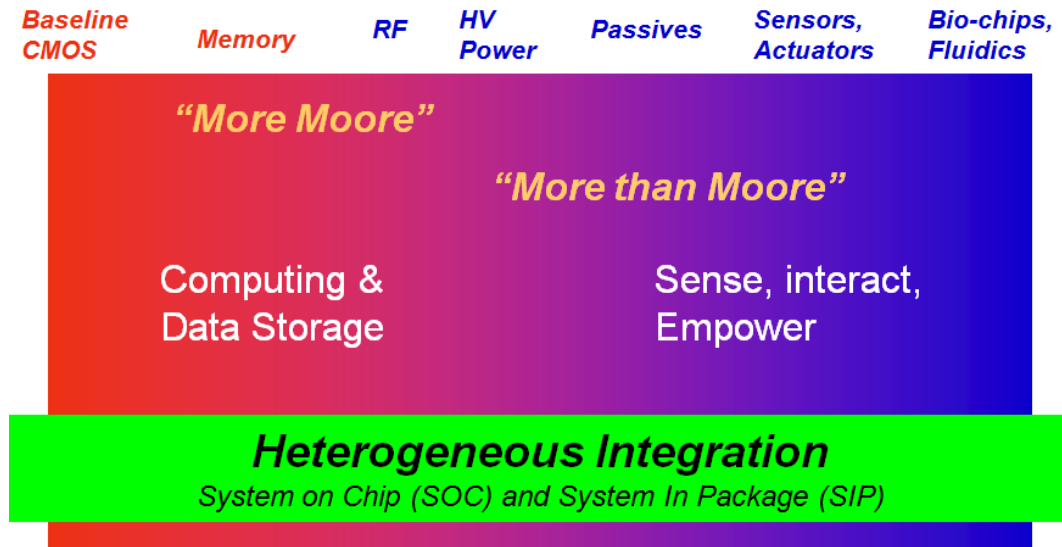


Figure F-1. “More-than-Moore” heterogeneous integration of functionality on the chip.

In today’s systems, the processor is connected to the other system components—power source, external memory, RF chips, sensors, etc.—on the motherboard, using wires made of copper. In an SOC paradigm, these system components would migrate directly onto the silicon platform—at first, vertically separated, and eventually stacked vertically as system design and manufacturing processes evolve to support this. This would optimize performance at the system level and extract much larger improvements in system performance than linear scaling alone is able to do. The first systems manufactured would likely integrate processor, memory, and communication chips; eventually, MEMS, sensors, and biologics would also be integrated. Advances in three-dimensional integrated circuits and silicon photonics, described in the previous section, would feed into SOC technology.

There will be an increasing emphasis on field-programmable gate arrays (FPGAs) and a shift away from application-specific integrated circuits (ASICs) as chip technology becomes more general purpose (Welser 2011; Pope 2011). This would also open up possibilities for mass customization of chips, produced inexpensively and programmed at the software level (Welser 2011; Jammy 2011)

Manufacturing Process

An SoC system will combine digital and non-digital (sensing, communication, and fluidics¹⁰) elements on the same platform; thus, suitable materials must be found for the new applications and integrated into the CMOS manufacturing technology. While leading manufacturers such as TSMC, Intel, and Samsung are in a competitive race to ramp up heterogeneous-integration methodologies for the silicon platform, incorporating new functionality will need cross-disciplinary work and new learning for the industry. More automation and standardization will be needed for the new processes introduced.

Manufacturers of SoC and three-dimensional integrated products will initially be more vertically integrated, which will cause big shifts in the highly modular and globally dispersed ecosystem of the semiconductor manufacturing industry. Further, processor-packaging technologies (flip-chip bonding) would be replaced with three-dimensional packaging technology. Three-dimensional packaging saves space by stacking separate chips in a single package, making it more economical for low-cost manufacturing.

Far-Term Technology Trends (“Beyond CMOS”)

The United States leads the world in research on “beyond CMOS” technologies.

Device and Materials

The limits of CMOS scaling have also infused an urgency into the vision of discovering new, highly scalable concepts for information processing and memory functions to enable orders-of-magnitude higher miniaturization than that possible using silicon CMOS devices. These concepts could be based on a new “token” (such as electron spin or molecular resistance) to represent electric charge as a means to represent information (Cavin et al. 2005; Bernstein et al. 2010; Welser et al. 2010).

The change to a new information-processing technology will likely be accomplished in two phases: in the first, the potential new technologies would have to be integrated with existing CMOS processes to extend chip functionality beyond what would be possible with CMOS alone—a hybrid technology. The second phase would complete the evolution to a completely new, multifunctional and scalable technology platform (ITRS 2010a). This second phase is at the basic stages of research, and it will likely continue past the 2030 time frame.

The new devices being explored for “Beyond CMOS” technology may perform processor or memory functions or in some cases, a combination of both functions in a universal device. They should ideally show significant advantages over ultimate scaled devices in power, performance, and density. They should also be capable of integrating

¹⁰ *Fluidics* is the use of fluids or compressible media to perform digital and analog operations similar to those performed by electronics.

with the CMOS process, to allow insertion into heterogeneous or hybrid systems, thereby enabling a smooth transition to a new scaling path (Welser et al. 2010). These goals are driving research in graphene, carbon nanotubes and nanowires, among other materials.

While many ideas are being pursued, a representative sample (based on demonstrated feasibility) is listed (Bernstein et al. 2010):

- *Field-effect transistor* (FET) devices that can operate at lower voltages, such as band-to-band tunneling FETs.
- *Nanomagnetics and spintronics* (Welser et al. 2010). This technology exploits the spin properties of electrons (both individual and collective oscillations). Recent advances based on magnetic spin properties include products like MRAM (Chen 2011a), which could be a key component in defense systems that require radiation-hard, non-volatile memory. Metal-based spintronics are likely to reach commercialization first, using a phenomenon called spin-torque transfer for storage (Welser 2011) and applications (called STT-RAM) (Chen 2011a; Jammy 2011). Semiconductor-based spin devices are still very much in the research stage.
- *Resistance-based memory devices* (Chen 2011a) or conductance devices (resistive random access memory, or ReRAM). Resistive memories will be very dense and easy to stack. Non-volatile memory integrated with logic is also being explored.
- *Single-electron transistors* (Mizuta, Tsuchiya, and Oda 2010; Rocco 2011). These are switching devices that use tunneling mechanisms to transport single electrons from source to drain. While these devices hold the potential of ultra-low-power electronics, significant obstacles remain in the variation control of threshold voltage before SETs can be used in large-scale circuits.
- *Molecular devices*. These are based on molecular switches—molecules that switch reversibly between two or more positions. The use of molecular switches as programmable diodes is the core technology underlying projected applications. Logic, memory, and interconnect functions have been demonstrated using molecular assemblies, but integration onto a circuit is still a long-term research goal. The United States is the leader in developing this technology, but Japan also has significant investments here.

Manufacturing Process

Bottom-up manufacturing processes such as directed self-assembly of molecules (currently shortlisted on the International Roadmap for further investigation) will start being incorporated into the existing CMOS platform for building heterogeneous devices and eventually play a larger part in improving process control at lower costs (Likharev

2011; Herr 2011; Merzbacher 2011). Currently, self-assembled structures of diblock copolymers are being used as an alternative to photoresists for sub-10 nm design features in design patterns (Herr 2011). However, the scale and scope of investment in the current manufacturing methods is such that a full shift to bottom-up manufacturing is predicted to be decades away.

A second challenge will be incorporating new materials onto the silicon platform in ways that their functionality can be fully exploited (Jammy 2010).

Software Trends: Electronic Design Automation and Modeling and Simulation

Tools

As circuits simultaneously miniaturize and become functionally diversified, the electronic design automation industry will require multidisciplinary teams comprising system architects and nanotechnology researchers, among others, to keep up with the hardware and computing changes needed over the next two to three decades (Gupta 2011). There will be a tremendous emphasis on the need for new design methodology and multiscale modeling and simulation tools.

“More than Moore” and three-dimensional “System-on-Chip” technologies will necessitate dramatic changes in the use of electronic design automation tools, as non-digital components begin to interface with digital components. This will necessitate new learning in sensors, fluidics, and related areas, as well as methods to optimize digital and non-digital parameters for improving performance.

As “Beyond CMOS” devices and circuits continue to scale down, there is an urgent need for multiscale modeling and simulation of phenomena ranging from material properties (thermal, transport, etc.) and device structures to circuit and system-level design; the need for molecular and atomic level simulation will also increase. High densities of device packing will necessitate the development of fault-tolerant computing architectures, such as those being explored using the Teramac (Culbertson 1997), a custom computer designed for architectural exploration by having three-quarters of its features contain defects. In the longer term, it is anticipated that computing architectures will draw from biological systems (Likharev 2011; Rocco 2011), focusing on massively parallel, adaptive systems. The DARPA project Systems of Neuromorphic Adaptive Plastic Scalable Electronics (SyNAPSE) aims to develop “cognitive computers” or “systems that simulate the human brain’s abilities for sensation, perception, action, interaction and cognition.” These systems borrow the structure of human neural systems.

Global Scan of the Microelectronics Industry

The electronics industry was one of the first high-tech industries to become globalized in its research, design, and manufacturing. As the technology got increasingly

complex and expensive manufacturing processes began to be required, lower cost manufacturing operations available to U.S. companies in Asian countries made offshore manufacturing an appealing option. The effect of this can already be seen in the substantial microelectronics manufacturing base established in Taiwan, Korea, and China. This section describes the current and future state of the global microelectronics industry and its potential implications for the national and economic security of the United States. These specific nations were chosen because of their relative dominance in the industry.

China

Over the past several decades, *as China's economy continues to grow, its role in the global microelectronics industry has become more important in terms of both production and consumer markets*. In August 2011, China, for the first time, passed the United States to become the world's biggest PC market (Fletcher 2011). The growing demand comes not only from increased government spending, but also from consumers and businesses, as a rapidly moving economy has been shaping the industrial landscape. The growing market is anticipated to increase investments from foreign chip and PC makers in this country. For example, Taiwan's Acer Inc. partnered with Chinese PC vendor Founder Technology group to use the Founder brand in China, a mutually advantageous venture.

China currently leads the world in long-term public investment in microelectronics and other strategic industries. The Chinese Academy of Sciences and the Ministry of Science and Technology (MOST) have invested about \$10 billion since 2003 in science and technology "megaprojects," including microelectronics projects focusing on core electronics components, high-end general-use chips, and large-scale integrated circuit manufacturing equipment and techniques (Alspector 2011).

In October 2010, the "Decisions of the State Council on Accelerating the Development of Strategic Emerging Technologies" (USITO 2011), released by the State Council, lists "Information Technology" as one of the first seven national strategic emerging industries that will be cultivated rapidly, focusing on "network infrastructures and internet equipment, the 'Internet of Things,' cloud computing, integrated circuits and new display devices, software and servers." The first industry fund for \$73 million was set up to create an Internet of Things industry in the Jiangsu province in 2010 (Peng 2010). However, even though large government investments and expansive policies have accelerated China's growth in the microelectronics sector, *industry analysts contend that Chinese IC companies are clustered at the low end of the value chain, working on peripheral products and imitating rather than innovating* (Chitkara 2010).

It is believed that China is not expected to out-innovate the West (Jammy 2011). Instead, *China is trying to replicate the U.S. technologies, but by doing it more quickly and less expensively*, with the same functionality at a lower cost. In 1980, the government

set up special economic zones to attract foreign investment; more recently, High-Tech Industrial Development Zones have been set up to attract foreign investment and technology from companies like Intel, IBM, AMD, Microsoft, and Cisco (FinPro 2010).

On the other hand, *protection of IP is a concern when doing business or participating in joint ventures with Chinese companies*. Instances of product tampering and counterfeiting of electronics products assembled in China have also compromised the safety and security of the defense (and consumer) electronics supply chain (Pope 2011).

Other possible threats to the United States include China's integration with Taiwan, which would have significant implications for U.S. economic and national security (Alspector 2011).

Japan

For decades, Japan has actively fostered the growth of its domestic microelectronics industry through national policy imperatives and a strong R&D foundation, and it will continue to do so in the future. Japan has several international partnerships and consortia in its semiconductor industry, such as the recent \$60 million fund for a collaboration between Toshiba, Intel, and Samsung to develop 10 nm semiconductor technology by 2016 (Battelle 2010).

Japan's Ministry of Economy, Trade, and Industry (METI) extensively funds nanotechnology research centers such as the recently created the Tsukuba Innovation Arena Nano (TIA Nano), a nanotechnology R&D center that supports collaboration between academia, government, and industry with a federal budget of \$361 million over 2 years (from 2009 to 2011) (Semiconportal 2009).¹¹ Among the heavily funded areas are nanoscale materials (graphene, carbon nanotubes and nanowires), instrumentation, and post-CMOS transistor technologies. Japan may be ahead of the United States in memory technology, and with large investments in multinational and national collaborations, this trend will likely continue for the next 5–20 years. However, *a vulnerability identified by experts is the lack of a strong connection between industry and the university system*, which can be essential for fruitful R&D in the microelectronics industry (Jammy 2011).

Taiwan

Taiwan is today the world leader in semiconductor foundry services. The Taiwan Semiconductor Manufacturing Company (TSMC) is the world's largest foundry company, with 2010 revenues averaging \$13.3 billion. Taiwan is growing in IC design

¹¹ With the budget, METI plans to build facilities such as foundries for MEMS and test production of devices, nano-measurement systems for measurement services, and labs. The 36.1 billion yen will be used for construction through March 2011, the end of next fiscal year. See <http://www.semiconportal.com/en/archive/news/main-news/090818-meti-mems-tsukuba-research-product.html>.

services with more than 270 design houses. Taiwan also leads in several other sub-sectors, such as IC packaging and assembly, consumer electronics, and communications products (Chen, Wen, and Liu 2011). Taiwan's Advanced Semiconductor Engineering (ASE), Inc., one of the world's largest providers of semiconductor packaging and assembly services (UK Department of Investment Services).

Taiwan's semiconductor industry started with a single company in 1985, the Taiwan Semiconductor Manufacturing Corporation. As the chip-making industry has become more horizontally integrated, competing on large volumes rather than customized products, Taiwan has reaped the full benefits of the outsourcing of U.S. semiconductor manufacturing, providing contract-manufacturing services to most of the global leading chip manufacturers. This has been aided by sustained government involvement in strategic planning. Its funding of this industry created a large and well-trained workforce in chip-making technologies and local industries that provide a variety of support functions (Jammy 2011). Most recently, the largest Taiwanese companies have entered into collaborations with EU organization IMEC, a leader in nanoelectronics research, and Dutch equipment maker ASML to establish an R&D center at the Hsinchu Science Park in Taiwan, the first of its kind in Asia (Steffora Mutschler 2008; Chen 2011b), a move that could leave Taiwan in a very strong position in chip manufacturing over the next decade or two.

In terms of investments, Taiwan has well-funded programs for developing "System-on-Chip" and next-generation wireless communications technologies (Government Information Office Republic of China 2010). All projections show Taiwan continuing to dominate the foundry space, while also growing strongly in communications technologies (IC Insights 2011).

Korea

Korea's microelectronics industry, dominated by Samsung, leads the global industry in wireless consumer products and the memory sector. The growth of the microelectronics industry in Korea is also the result of carefully crafted visionary planning and of *reaping the full benefits of learning by imitation*. Korean firms, particularly Samsung, are aggressive in their global market research and recruitment and workforce development. Much like Taiwan, Korea has over the past decade tried to establish a position in research and development of microelectronics and nanoelectronics technologies, leveraging international collaborations and customer-supplier relationships to gain technological expertise. Samsung most recently announced plans to collaborate with IBM, U.S.-based GlobalFoundries, and French chip maker STMicroelectronics to develop a process technology for 28 nm processors (Battelle 2010).

In terms of emerging areas, *Korea is investing heavily in fundamental materials research, focusing on graphene and carbon nanotubes.* It is possible that within the next

5–10 years, Korea will be the first country to commercialize graphene for its simpler uses (Welser 2011; Doering 2011). Industry experts believe that given Korea's *ability to "leapfrog" technologies* (previously demonstrated in the steel and automobile industry), coupled with a sharp increase in the number of quality research papers from the country over the past decade (Welser 2011), the United States needs to be aware of Korea as future competitor in the microelectronics industry.

European Union

The EU's strength lies in its focus on strategic public-private partnerships, such as the CEA-LETI in France and the Fraunhofer Institutes of Microelectronics in Germany, that cross multiple disciplines, while training students who then go on to lead the technology development in member companies (see 3.B.2). They also have coordinated efforts (Framework programs) in funding specific areas of interest, such as Future and Emerging Technologies (FET) Flagship (FET 2011) programs (set to receive up to €1 billion over 10 years), where graphene has been chosen as one of six pilot research areas (Doering 2011). The general sentiment among experts in the field is that *research programs in the EU mirror those in the United States*, leaving little room for surprises (Welser 2011; Theis 2011).

Other Factors

This section discusses several global factors, external to technology development and manufacturing, that were identified as having the greatest potential for affecting future trends in the microelectronics industry over the next 5 to 20 years. These are intellectual-property issues, supply chain dynamics, government funding and regulations, education, and the consumer market.

Protection of Intellectual Property and Know-How

Competitiveness in advanced manufacturing industries depends on capabilities and expertise built on years of experience—these allow companies to produce the best product at optimal cost, quality, and speed (Jammy 2011; Pillai 2011). Much of this learning is embodied in patents and trade secrets, but some is unwritten, tacit knowledge. As manufacturing increasingly takes place in a global arena, protection of intellectual property has become difficult because (1) it is not enforced uniformly and (2) countries have vastly different concepts of intellectual-property protection than the United States (Rocco 2011). For instance, *in China, a policy of "indigenous innovation" makes it possible to patent an innovation that looks identical to a U.S. patent* (Rocco 2011; Pope 2011). The globalization of the microelectronics industrial base means that companies are part of myriad customer-supplier relationships and joint ventures crossing international borders, where it is very difficult to regulate or control the flows of information between

companies (Pope 2011). Companies need to implement sophisticated cyber-security measures to protect themselves against more aggressive forms of intellectual-property theft such as industrial espionage (Pillai 2011; Pope 2011).

Supply Chain

As mentioned earlier, there has been a steady erosion of semiconductor manufacturing fabs out of the United States over the past two decades, resulting from increasing costs of manufacturing, coupled with easy access to government subsidies, an educated workforce, and access to new markets in other countries. *The loss of a manufacturing base in a sector where the United States is a market leader has significant implications for future economic security*, apart from a dwindling supply chain and loss of workers skilled in manufacturing. Further, *for leading companies in the sector, the cost of R&D with every successive technology generation is growing exponentially, leading to a slow winnowing of the field*, as fewer companies can survive and stay competitive (Welser 2011; Anonymous 1 on Semiconductors 2011; Herr 2011; Doering 2011; Jammy 2011)

Other factors that have influenced the growth of the semiconductor manufacturing industry globally include the presence of a strong and demanding customer base (because product sales are stronger in the Asia-Pacific and developing countries than in Europe and North America, leading manufacturers have been slowly growing their presence in these regions), investment in physical and cyber infrastructure that accelerates the pace of technology adoption, and investment in standards and protocols (Jammy 2011).

Role of the Government Policy and Investment

Over the past 20 years, semiconductor manufacturing has grown rapidly and expanded in countries such as *Korea, Taiwan and parts of the EU where the government has nurtured the advancement of the industry via direct policies*. Taiwan is often cited for over 20 years of sustained, comprehensive investments that capture everything from the manufacturing technology to human capital to fostering of local small and medium enterprises that support the main industry (Jammy 2011). Such policies have placed these countries in a very favorable position to take advantage of the anticipated boom in wireless technologies over the next two decades.

On the other hand, the U.S. industry has seen a brisk off-shoring of manufacturing facilities over the past 20 years. Part of this is an effort to access growing markets in Southeast Asia and other developing countries and take advantage of the trained workforce there; however, in the case of the very capital-intensive semiconductor industry, an overriding factor is tax breaks and other incentives provided by foreign governments, which subsidize the cost of building new fabrication facilities by over \$1 billion (Welser 2011; Anonymous 1 on Semiconductors 2011) U.S. chip manufacturer

Intel Corp recently opened a \$1 billion chip testing and assembly plant in Vietnam and a \$2.5 billion subsidized manufacturing plant in China, which cost about \$2–\$3 billion less than an equivalent facility in the United States (Battelle 2010). In terms of providing tax breaks for new businesses as well as tax credits for performing R&D, *U.S. tax regulations are seen as uncompetitive and cumbersome.*

Funding of Long-Term Research

Advanced manufacturing technologies are heavily derived from research in the basic physical and biological sciences. Long-term or disruptive breakthroughs in the areas of nanoscale electronics and other computing technologies will need sustained funding at every level, starting from the basic science (in areas like characterization of new materials, measurement and instrumentation at the nanoscale, etc.) to manufacturing technology and pre-competitive standardization (Likharev 2011; Herr 2011; Doering 2011). Public-private partnerships (such as the Fraunhofer Institutes in Germany and the ITRI Institute in Taiwan), industrial clusters, and resource programs allow for accelerated progress in these areas.

Global Semiconductor Industry Scenarios, Near Term

It is expected that the current paradigm of CMOS scaling will dominate through approximately 2018. During this time, the high costs of R&D and manufacturing will lead to increasing consolidation and risk aversion in the industry. This is reflected in a significant decrease in venture funding and access to capital for companies in this sector (Trew 2011). *More innovation (proportionally) in this sector will likely occur in other countries (concentrated in Korea, Japan, Taiwan, and the EU); a diversion of talent from the United States is already being observed.* The United States will be the leader in innovation; however, it is possible that the rate of innovation may stagnate.

Only those countries and companies with the greatest financial resources can continue to afford manufacturing to the limits of silicon CMOS scaling. Table F-1 shows the power rating by company by country. The power rating is based on a company's 300 mm capacity, which is the rate of production of 300 mm wafers by the fab (which in turn is reflective of the equipment and technological sophistication of the overall fab). The power rating is an indicator of capability for leading-edge manufacturing and capital spending. Based on this rating, 7 of the top-10 companies are Asian and 3 are U.S. (Americas) companies.

Table F-1. Power rating of semiconductor companies worldwide based on their capital spending and capacity for leading-edge high-volume manufacturing.

"Power" Ranking of 300mm Wafer Capacity Leaders (2010)

300mm "Power" Ranking	Company	Headquarters Region	300mm Capacity Rank for 2010	Capital Spending Rank for 2010	300mm "Power" Rating*
1	Samsung	Korea	1	1	2
2	Intel	Americas	3	3	6
3	TSMC	Taiwan	5	2	7
4	Hynix	Korea	2	6	8
5	Toshiba/SanDisk	Japan/Americas	4	5	9
6	Micron	Americas	6	8	14
7	GlobalFoundries	Americas	10	4	14
8	Nanya	Taiwan	9	7	16
9	Elpida	Japan	7	10	17
10	UMC	Taiwan	12	9	21
11	Renesas	Japan	14	12	26
12	Powerchip	Taiwan	8	18	26
13	IBM	Americas	13	15	28
14	Texas Instruments	Americas	17	11	28
15	SMIC	China	18	13	31
16	ProMOS	Taiwan	11	21	32
17	STMicroelectronics	Europe	20	14	34
18	Fujitsu	Japan	16	22	38
19	Rohm	Japan	22	17	39
20	Panasonic	Japan	19	23	42
21	Winbond	Taiwan	15	28	43
22	Xinxin	China	21	29	50
TOTAL		—	—	—	—

*Combined capacity and capital spending rankings (lower figure is best)

Source: IC Insights (2011).

Rising costs may also favor the growth of low cost roll-to-roll methods of manufacturing; however, they will play a complementary role to CMOS electronics during this time frame, being primarily used for large-area applications.¹²

A significant amount of R&D conducted in this industry over the next decade will be collaborative across nations, necessitated by rising costs. Such partnerships also provide an opportunity for foundries to develop internal R&D capability that benefits their ability to be competitive manufacturers.

The shrinking of the domestic supplier base in the United States will continue to pose a security threat to the defense electronics industry and perhaps also to the economy, as chip companies and equipment makers move out of the United States to Southeast Asia. This will have a negative impact on long-term research in the United States, especially in areas such as modeling and characterization of new materials and instrumentation.

¹² Roll to roll is the process of creating electronic devices on a roll of flexible plastic or metal foil.

Over the next decade, the semiconductor market will be driven by mobile- and cloud-computing applications, the need for power-efficient devices, improved connectivity, and increased information handling. Migration of IT and computing needs to emerging cloud-computing services will necessitate robust data handling and security measures.

Global Industry Scenarios, Medium Term

Two complementary technology directions are expected to come to fruition in the medium term—the “System-on-Chip” concept, which will integrate memory, computation, sensing, and transmission functions directly in the chip, and the development of an infrastructure (sensor nets, powerful and adaptive communication and computation platforms, etc.) for small, locally connected intelligent systems, and ubiquitous computing leading to cyber-physical systems, or an “Internet of Things.”

On the application side, *nanoelectronics will become pervasive* in new sectors such as energy (smart-grid control, energy-efficient buildings), transportation (autonomously controlled vehicles), and medicine (implantable devices, prosthetics, and biocompatible imaging systems, all of which require engineering of safe organic-inorganic interfaces), and others.

Heterogeneous integration will put increasing emphasis on design functionality, flexibility, and innovation at the system level. A big challenge will be to customize chips in innovative ways (i.e., programmable functionality and mass customization using chip components). An example of system-level innovation of this type is the iPod, which integrates off-the-shelf hardware to build a customized product. In the platform-dependent mobile technology, companies that manufacture the cores as well as the platform (Samsung, Qualcomm) may lead the way toward mass customization of chips.

As with any new technology, these systems will at first be vertically integrated, which could be a chance for countries investing in the technology (the United States has a lead in three-dimensional packaging technologies; the EU has large investments in the area of photonics) to lead the market before the technology matures enough for modular manufacturing, and cost-efficient manufacturers move into the supply chain.

Global Industry Scenarios, Long Term

In the longer term (20+ years), the current methods of semiconductor manufacturing will no longer be sustainable unless cost-lowering disruptive trends are able to take hold. Even with the sunk cost in CMOS technology, the cost and energy consumption of the manufacturing process will in all likelihood make it unsustainable by then. This could accelerate the development of new manufacturing methods, where device materials are self-assembled utilizing nanoscale phenomena. Use of self-assembly

in chip fabrication is currently being explored in the patterning process, but intense, long-term research is needed for self-assembly and other bottom-up fabrication methods to gain traction as manufacturing technologies.

Another consequence of the high cost of innovation within the CMOS framework could be the rise of low-cost, flexible electronics. The increasing applications of this technology in other fields (such as photovoltaics and other large-area applications) will allow it to advance and become cost effective.

Barriers to Projected Growth of Sector

There are several barriers to achieving expected progress in the 20 year time frame. First, the *high capital investment in the manufacturing process serves as a barrier to innovation.* There is significant resistance from most high-volume manufacturers to making radical shifts in manufacturing materials and processes. At a more basic level of R&D, more research into developing new materials databases and molecular-scale simulation tools is needed. ICME and similar programs may help with this. Second, *experts interviewed also commented on the lack of trained engineers in the United States; attractive opportunities in other countries are drawing many foreign students back to their home countries.* Finally, new *computing architectures, circuit designs, and devices* expected to evolve in the 20-year time frame *need fundamentally different modeling and simulation tools* to support development, from molecular modeling of nanoscale processes to quantum- and parallel-computing architectures. *Simulation capability lags the pace of technology development.*

Appendix G.

Advanced Materials and Integrated Computational Materials Engineering

From the discovery of iron and bronze in ancient times to later achievements in fuels and macromolecular synthetics, advanced materials have a history of opening new vistas of technology. To this day, they continue to provide the essential building blocks of numerous end-use products ranging from household items to critical defense applications. They remain a gateway to new manufacturing technologies as well as a driver of novel processes that can herald the development of revolutionary products.

Variegated categories are commonly employed to describe advanced materials, often based on material class, properties, or application. In this appendix, a broad definition is used to allow study across these categories: advanced materials possess new or innovative internal structures that yield superior properties and facilitate disruptive or transformative changes in manufactured products (Mathaudhu 2011; Moskowitz 2009). This definition implies a natural evolution of materials classes, properties, and applications over time due to scientific progress as well as shifting economic and strategic priorities.

The appendix begins with a rationale for including advanced materials in our study. To provide context necessary to understand the possible futures of advanced materials, a brief outline of areas of advanced materials and the corresponding status of global R&D follows. Advanced materials groups that may significantly influence the future of advanced manufacturing, as identified through discussions with subject-matter experts are then detailed. Then, an in-depth description of the topic of integrated computational materials engineering (ICME) is provided, including potential R&D breakthroughs that could result in the next 20 years.

Rationale for Studying Advanced Materials

The ubiquity of advanced materials used in various stages of advanced manufacturing may have potential impacts on national and economic security. Numerous defense systems, including armor, weapons, aerospace, and vehicle technologies, rely heavily on materials advancements. Furthermore, the security of an appropriate materials supply chain, including raw materials, is necessary to sustain progress in the advancement of defense capabilities and in continued domestic production of advanced materials and products for essential civilian uses. For example, rare-earth elements are

vital in the production of permanent magnets, which are critical to applications ranging from wind turbines for energy generation to electronics for communications.

Countries across the globe, including the United States, are investing significantly in advanced materials R&D. For example, the European Framework Programs have heavily supported materials research with specific thrusts in nanomaterials, manufacturing, and energy (Samaras, Victoria, and Hoffelner 2009; NMP Expert Advisory Group 2009). The Chinese Academy of Sciences has also recently released a roadmap to 2050 of advanced materials science and technology that suggests a sustained commitment to research in this area (Lu et al. 2010).

Advanced materials developments can also provide key enabling technologies that may ultimately be used across multiple industries. Materials advancements in fields such as biomaterials or optoelectronics may enable new paradigms of medical treatment and display technologies. Consequently, new processing techniques will be needed to support the new technologies and products. In the case of optoelectronics, new roll-to-roll processing capabilities may supplement prevailing batch-processing techniques and usher a new generation of flexible optoelectronic devices.

Global Status of Advanced Materials

Research in advanced materials is active worldwide, with different countries excelling in a variety of subfields. Interestingly, materials is cited as an area in which collaboration easily occurs internationally since export controls and the International Traffic in Arms Regulations (ITAR) are typically less restrictive with respect to research of component parts and materials than the systems in which they are used (Anonymous 1 on Advanced Materials 2011). Moreover, the interdisciplinary nature of materials science research lends itself to collaboration across countries with different strengths. To provide further context regarding the importance of advanced materials, we briefly discuss ten areas of materials research and compare the efforts of the United States with global leaders in the research of these materials.

Advanced materials are commonly grouped by material class (e.g., metals or composites), application (e.g., energy or defense), or properties (e.g., mechanical or electrical). While these classifications are not mutually exclusive, they provide a reasonable starting point from which to assess the state of materials R&D. Here, a brief review of the global status of R&D is provided based on the materials classes used in the National Research Council *Globalization of Materials R&D* report (2005):

- *Biomaterials*—In this document, biomaterials are defined as materials developed for *in vivo* application. Just over a decade ago, the United States was recognized as a “clear leader” in this field, (NRC 1998) but, since then, focused efforts by other countries have expanded. Nonetheless, the largest commercial

market for medical devices is the United States, which has helped prevent a diminishing domestic effort in the field (NRC 2005). A recent Battelle R&D Magazine Survey found that 73% of respondents perceived the United States as a leader in biomaterials compared with Germany, Japan, and China (Battelle 2010). Nonetheless, the Seventh European Framework Program has outlined “materials for health” as a research priority (Kiparissides 2009), and the Chinese Academy of Sciences cited its large, aging population, including 60 million disabled people as a driver for its continued interest in biomaterials (Lu 2010b).

- *Catalysts*—A catalyst is a material that promotes a chemical reaction without becoming a part of the product. This research area has been stagnant in the United States since 2000, but climbing on the global scale. China and the Netherlands have developed centers of excellence on the topic (NRC 2005) and India, too, recently established one in 2006.¹ Russia has had an institute dating back to 1958 with a reported 350 research scientists.² A recent bibliometric analysis by the World Technology Evaluation Center (WTEC) shows that the United States had a dominant position in catalysis research from 1996 to 2005, but Western Europe led the world in total papers published and citation impact during that period (Davis et al. 2009). The WTEC report also cited an aging U.S. catalysis research infrastructure compared with that of East Asia and Europe as cause for concern in maintaining competitiveness in this field.
- *Ceramics*—The primary countries for advanced ceramics research are: the United States, the United Kingdom, Germany, and Japan, which have all participated in ceramics-oriented technology foresight activities in recent years (Rodel et al. 2009). Energy accounts for 10–30% of production costs thus energy-saving techniques will be important to preventing further loss of leadership (ECORYS Nederland BV 2008). Primary growth areas will be located in markets such as electronics (e.g., as capacitors, inductors, and piezoelectric devices), construction, automotive, and other industries that require good resistance to corrosion and good mechanical properties at high temperatures (Moskowitz 2009).
- *Composites*—Composites are defined here as two or more physically or chemically distinct materials that contain an interface of separation, which helps distinguish the constituents. Common examples include metal-matrix composites and cermets. Japan and the United States are leaders of carbon fiber composites with 70% and 15% of global production, respectively (UK

¹ Additional information on the center in India can be found at its website: <http://www.nccr.iitm.ac.in/>.

² Information on the Russian Institute of Catalysis was retrieved from the institute’s website at <http://www.en.catalysis.ru/block/index.php?ID=19>.

Department for Business Innovation and Skills 2009). Composites research is on the decline in the United States as a result of cutbacks in ballistic missile and reentry programs; this area has been picked up in countries, including France, Korea, Taiwan, China, and Japan (NRC 2005). Due to anticipated growth across a variety of sectors, especially aerospace and wind energy, other countries including Germany, France, and Spain are growing their research in composites (UK Department for Business Innovation and Skills 2009).

- *Electronic and optical-photonic materials*—The electronics industry and supply chain are highly globalized, making direct comparison among countries difficult, but R&D in materials and processes of semiconductor devices remains strong in the U.S. Primary competitors are Japan and Korea, which excel in their research of displays and optical memories.
- *Magnetic materials*—In 2000, the United States was considered to be playing catch-up with other countries on research of magnetic materials and magnetism (NRC 2005). Hard ferromagnet research is still centered in the United States and Europe (primarily Germany), but Japan and Europe lead in soft ferromagnets. Biomagnetism is being studied in the United States, Canada, Australia, and Europe. Magnetic cooling work is taking place in the United States, Canada, Japan, Europe, Russia, China, and Hong Kong. The United States permanent-magnet industry is essentially nonexistent due in large part to its lack of raw, rare-earth elements.
- *Metals*—Research in metals production, processing, and development has been on the decline since the late 1990s, with only minimal alloy development occurring in the period since then (NRC 2005). In part, this relates to decreasing use in applications such as aerospace or even sporting goods, where traditional metals are being replaced by lightweight composites (Lu 2010a). In metals R&D, computer-based modeling is one of the U.S. strengths, but Japan and Europe are quickly gaining ground (NRC 2005). Metallurgy, a more traditional materials research area, has lately suffered in part from a lack of classically trained materials engineers in developed nations (Engineering and Physical Sciences Research Council 2008).
- *Nanomaterials*—The area of nanomaterials only recently emerged as a subtopic of nanotechnology but has been growing rapidly, with the United States maintaining a “modest lead” according to a 2005 report (NRC). Much of the innovation results from small or start-up companies, which are not anticipated to establish as strong an R&D base as those in other locations, such as Europe, which has invested in fundamental R&D at universities as part of its European Framework Programs (NRC 2005; NMP Expert Advisory Group 2009).

- *Polymers*—The United States maintains a leadership position in polymers, but Asia and Europe remain potential competitors (NRC 2005). In particular, interest in polymers is growing due to applications in energy (e.g., solar cells), composites, and smart materials (e.g., conductive polymers) (NRC 2003b; Adams and Pendlebury 2011).
- *Superconducting materials*—On the whole, the United States and Japan lag behind the asia-pacific region (including China, India, and Korea),³ but certain companies in the United States do stand out as leaders in particular areas of design, manufacture, or characterization (Abetti and Haldar 2009). While magnetic resonance imaging is the largest commercial application at this time, other potential applications include energy storage, solar cells for liquid crystal displays, and thin-film resistors in integrated circuits (Moskowitz 2009).

Worldwide efforts in materials research are expanding. The growth in publications and citations on materials science topics places the United States, EU-15,⁴ Japan, Taiwan, Korea, China, and India at the top, according to recently compiled impact data from the Web of Science index from 2005 to 2009 (Adams and Pendlebury 2011). The EU remains a strong competitor with much of its previous efforts summarized in the European White Book on Materials Science (Rühle 2001) and more recently with the European Framework Programs.

Areas for Further Examination

Discussions with subject-matter experts generated a number of advanced materials topics that they believed to have a potentially high impact on the future of advanced manufacturing. While ICME was selected for further study in this work due to its prevalence in discussions with experts, some of the other most oft-discussed topics warrant additional examination:

- *Critical and Strategic Materials* are a class of elements and material commodities that are of economic and strategic importance but have an uncertain or limited future supply. Associated supply-chain issues are described in detail, along with options for addressing them, in the sidebar “Critical and Strategic Materials Supply Chains.”

³ See press release for 2011 report by Global Industry Analysts: <http://www.strategyr.com/pressMCP-6535.asp>.

⁴ Before the accession of 10 candidate countries into the European Union on 1 May 2004, the EU15 comprised the following 15 countries: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom. (Source: OECD, “Glossary of Statistical Terms,” <http://stats.oecd.org/glossary/detail.asp?ID=6805>.)

Critical and Strategic Materials Supply Chains

Critical materials are a class of elements and material commodities that are of economic and strategic importance but have an uncertain or limited future supply. Currently, the United States is heavily reliant on imported materials such as tungsten, but there are others, including antimony, arsenic, bismuth, fluorspar, indium and rare earth elements (REEs), of which there is nearly no domestic production. Yet they are essential constituents in many key defense-critical applications (e.g., precision-guided munitions and travelling wave tubes for communications) and in other sectors as batteries for hybrid vehicles and catalysts for pollution control or fuel refining, among many others. As supply chains grow increasingly fragmented and export restrictions from some nations place an additional burden on manufacturers, the United States faces a mounting vulnerability to price fluctuations, as well as supply shortages, particularly in high-growth industries such as lithium batteries.

Due to the waxing and waning interest over the years regarding materials supply-chain issues, information on supply and demand is often inconsistent or incomplete, making it difficult to forecast needs. While extensive data are available for elements like platinum that have mature markets, newly critical elements such as REEs and lithium do not have well established information on their life cycles and availability. Consequently, this leads to uncertainty in predicting future critical materials supply-chain scenarios. This uncertainty is complicated by access to critical materials being influenced by a variety of geographical, political, and economic factors. A wide range of potential future environments could affect the REEs supply chain. In the worst case, China continues to dominate global supply and imposes further export restrictions and taxes, resulting in widespread shortages of REEs. On the other hand, it is also possible that domestic production comes online as demanded, thereby reducing U.S. reliance on imports.

One recent proposal to help understand the range of scenarios includes the simulation of conflicts over minerals and materials in relevant Department of Defense war games (Parthemore 2011). This would help determine potential strategic threats from longer term shortages while providing policy makers with additional context for decision-making. Such an approach could help the United States find long-term options to address the barriers, highlighted below, amid vacillating interest in the topic:

- **Education.** Despite previously being at the top of global minerals research, U.S. policies in the early 1990s led to a large reduction in the number of U.S. programs and universities still working in this area (Industrial College of the Armed Forces 2008). Since then, other countries such as China and Japan have grown in their capabilities. Beyond the educational needs for growing our own domestic supply, materials education in substitution and recycling approaches is also lacking.
- **Workforce development and training.** A recent National Research Council panel suggested that the low number of students and high number of upcoming retirees signals a possible need for increasing the capacity to meet future requirements (NRC 2008c).
- **Substitution and recycling.** Since the closure of the U.S. Bureau of Mines in 1996, R&D in minerals extraction, processing, and health and safety has declined. At the same time, the EU is recognizing the importance of substitution and recycling of materials as evidenced by recommendations to increase R&D in these fields in the recent report, "Critical Raw Materials for the EU" (2010).
- **Intellectual property (IP).** While U.S. lighting manufacturers hold key IP rights for fluorescent lighting phosphors, almost all the key patents for permanent-magnet production are owned by Chinese or Japanese interests, even though these magnets were originally invented in the United States (DOE 2010; Martin 2010). Maintaining control of the value chain will require appropriate protections of IP.
- **Data collection.** Accurate and timely data are needed but at present are unavailable at the detail and depth needed for informing decisions on national mineral policy (NRC 2008c).

- *Materials for Energy* are those related to energy conversion, transmission, storage, and efficiency and new technologies such as energy-harvesting devices. Ultimately, this area is driven by the desire to optimize the energy infrastructure and reduce environmental pollution. Specific areas of R&D include LEDs, lightweight structures for transportation, superconducting devices, energy storage, solar power technology, and fuel cells.
- *Functional Materials* are designed for components requiring specific physical or electrical material properties, rather than the more traditionally considered structural or mechanical properties. Functional materials can be found in all material classes, from polymers to metals and ceramics.
- *Smart Materials* can be controlled by external stimuli to manipulate properties such as geometry and electrical conductivity. Examples include piezoelectrics, shape-memory alloys, self-healing materials, magnetostrictive materials, tunable dielectrics, and electroactive polymers.
- *Primary Metals* such as aluminum are energy intensive to make and also produce environmental pollutants. Moreover, demand for aluminum decreased as a result of the recent recession, leaving 40% of domestic aluminum smelting capacity unused as of June 2011 (USGS 2010). Because of high energy and environmental costs associated with production, some experts expressed concern over the domestic industry's ability to restart as demand returns.

Integrated Computational Materials Engineering

Recently, concepts of materials design, processing, and manufacturing have converged into a field of integrated computational materials engineering (ICME), which aims to reduce the time and cost necessary to move from conception to creation of new materials. Concomitant reduction in manufacturing costs, improvements in prognosis for materials lifetimes, and greater ability to respond to changing market demands may also be realized with ICME. A recent report of the National Research Council (2008b) formally defines ICME as “the integration of materials information, captured in computational tools, with engineering product performance analysis and manufacturing-process simulation.” This integration involves multiple models with a database of information and systems engineering analysis tools, which are available to the user via a graphical interface. Although currently in a nascent stage of development, ICME has already demonstrated an ability to loosen the constraints on product design and manufacturing processes by linking our understanding of materials phenomena, from the quantum to the bulk scale.

While there is still no consensus on the exact definition of the field, a community is evidently forming around the concepts of ICME and continues to grow globally. Future

growth of ICME could enable the development of advanced materials, which have afforded the U.S. a significant competitive advantage in the global market (NRC 2008b).

History of Integrated Computational Materials Engineering

Although the term “ICME” has only recently emerged, the idea of unifying product and materials design has some of its early, coordinated roots at the 1987 Army Sagamore Materials Conference, which featured international experts discussing a systems-based approach to materials innovation (Olson, Azrin, and Wright 1987). Additional visionary dialogues were also held at the 1993 Gordon Research Conference on Physical Metallurgy (Olson 2011).

Discussions continued at a 1998 NSF-sponsored workshop, “New Directions in Materials Design Science and Engineering,” which identified the need for a change in culture to foster simulation-based design of materials and ultimately a more integrated approach to design of materials and products (NSF 1998).

Recent Federal initiatives have also highlighted the interdisciplinary work leading to ICME. One example is the 2006 NSF-sponsored workshop, “From Cyberinfrastructure to Cyberdiscovery in Materials Science: Enhancing Outcomes in Materials Research, Education and Outreach” (Billinge, Rajan, and Sinnott 2006). It brought together the materials community, including experts from other scientific domains that pioneered the use of cyberinfrastructure, to discuss future needs and strategies. Ultimately, a number of critical issues were identified, including rewards, standards, sustainability of data, databases and software, effective sharing, education and training, and access to computational resources on different scales.

More recently, an NSF Blue Ribbon Panel on Simulation Based Engineering Science identified several impact areas such as medicine, homeland security, and materials. The report recommended actions to accelerate the field. Among them were greater integration of modeling and simulation with education to broaden curricula and introduce students to more interdisciplinary problems (NSF 2006).

A World Technology and Evaluation Center study later examined international efforts in the area of simulation-based engineering and science (SBE&S) (Glotzer et al. 2009). The panel found that SBE&S activities abroad compete with or lead the United States in areas ranging from health to energy and sustainability. Opportunities to strengthen U.S. capabilities included making investments in industry-driven partnerships with universities and national laboratories, as well as in new approaches to education and training.

One of the major milestones for ICME in recent years came with the release of a study by the National Academy of Engineering’s National Materials Advisory Board (NMAB). The NMAB committee on ICME outlined a plan for the future to help fuse the

seemingly disparate activities of materials science and materials engineering, along with more holistic and computationally driven product development (NRC 2008a). Despite its promise for the future, ICME was identified by the group as being in its infancy.

In June 2011, the White House Office of Science and Technology Policy announced the Materials Genome Initiative for Global Competitiveness as part of its Advanced Manufacturing Partnership (NSTC 2011). Its aim is to reduce product development time through infrastructure and training improvements that will make advanced manufacturing more economical and efficient. Thus far, four Federal programs included as part of the initiative are housed at the National Science Foundation, the Department of Energy, the Air Force Research Laboratory, and the Office of Naval Research.

Efforts aimed at educating the research community on ICME are also emerging. Northwestern University is piloting a courses-based, Master's certificate program in ICME that began in the fall of 2011.⁵ Also, the University of Michigan, in partnership with the NSF, offered a two-week summer school in July 2011.⁶ These activities acknowledge the increasing need for training in ICME concepts as discussed in many previous reports (Allison 2011; NRC 2008b, 2004a).

Another indication that the field is evolving is that the first world congress on ICME occurred in July 2011 in Seven Springs, Pennsylvania, where more than 200 scientists gathered to attend from at least 11 countries around the world.⁷

Current Examples and Successes

Some early examples of ICME have proven beneficial to organizations that experimented with this approach. In some cases, a high return on investment was noted, ranging from 3:1 to 9:1 (NRC 2008a). One of the earliest implementations of ICME concepts was with the DARPA accelerated insertion of materials (AIM) program that began in 2001. This initiative was created with the goal of establishing new frameworks for the integration of tools that would quickly and inexpensively develop and qualify new materials and processes.⁸ Teams were assembled from original equipment manufacturers (OEMs), small companies, universities, and government laboratories to begin building

⁵ Further information on the Northwestern University program can be found at the Department of Materials Science and Engineering website: <http://www.matsci.northwestern.edu/gradinfo.html#msicme>.

⁶ Additional details on the summer school can be found on the archived University of Michigan website: <http://www.umich.edu/~mctp/SciPrgPgs/events/2011/SS11/index.html>.

⁷ For a list of conference talks, see <http://www.tms.org/Meetings/Specialty/ICME2011/PDFs/ICME-advanced.pdf>. Proceedings can be accessed at <http://www.wiley.com/WileyCDA/WileyTitle/productCd-047094319X.html>.

⁸ A more thorough treatment of the results of the DARPA-AIM program is reported in a study produced by the National Materials Advisory Board, "Accelerating Technology Transition: Bridging the Valley of Death for Materials and Processes in Defense Systems," available at: http://www.nap.edu/catalog.php?record_id=11108.

the knowledge bases for system design, including databases; microstructure; modeling and simulation tools; linkages between products, processes, and characterization tools; and communication protocols (McDowell and Olson 2008; NRC 2004a). Through this work, Pratt & Whitney demonstrated the ability to reduce forging weight by 21% while concurrently increasing disk-burst speed by 19%, and GE showed that its approach could accelerate disk-alloy development by 50% (Cowles and Backman 2010). Following the initial DARPA AIM investment, the ONR/DARPA “D3D” Digital Structure Consortium was formed with the purpose of higher fidelity microstructural characterization and simulation to support the AIM methodology (Olson 2011; Kuehmann and Olson 2009). Ultimately, these two phases of AIM led to the first fully computationally designed and qualified material, the Ferrium S53 landing gear steel, which reached flight in December 2010 (Kuehmann and Olson 2011).

Another commonly cited example from industry is the Ford Motor Company’s virtual aluminum castings (VAC) methodology that was used to produce an automotive aluminum cylinder head (NRC 2008a; Allison et al. 2006). Unlike traditional approaches where material choices and properties are static to the mechanical designer, the VAC methodology accounted for variance within material properties that resulted from processing techniques. This information was carried through the mechanical design assessment, ultimately allowing manufacturing simulations to be used as inputs for lifetime prediction. Consequently, significant rework and testing was avoided by adopting this computer-aided engineering (CAE) approach that simulated the design, casting, heat treatment, and durability testing of virtual components before actual fabrication (NRC 2008a; Allison et al. 2006). VAC achieved a number of milestones, among them the application of several models depicting structure as well as physical and mechanical properties, the efficient linking of these models, the allowance of spatial material properties considerations, and extensive validation of the models.

Livermore Software Technology Corporation, ESI Group, Naval Surface Warfare Center, Knolls Atomic Power Laboratory (Lockheed Martin Corporation), Toyota Central R&D Labs, QuesTek, and Boeing, among others, have also employed ICME concepts of integrating materials, component design, and manufacturing processes as described in the National Materials Advisory Board Study with the National Research Council (2008a). Major manufacturers as well as small companies, usually with government sponsorship, have utilized an ICME approach and realized its benefits.

In the last 5 to 6 years, efforts in developing ICME have continued. One example is with small businesses and software companies that have helped transition code from the laboratory to large industry through Small Business Innovation Research-supported work (Anonymous on ICME 2011). One expert suggested that defense labs could also accelerate ICME by being early adopters of the philosophy (Brinson 2011).

Technology Trends: Near Term

Experts were consulted to identify potential breakthroughs and advances in ICME that may occur in the next 5–10 years. Breakthroughs included both evolutionary and revolutionary progress that could likely occur over the prescribed time lines. Three themes emerged from the discussions with experts: design, data, and technology.

Design

Traditionally, product design requires that materials satisfy a predetermined set of property and performance requirements (Ashby 2005). While design engineers do their best to avoid narrowing their list of potential materials until as late as possible in the design process, in practice, they are left with a static list of material choices well before product optimization. Typically, material choice is optimized through combinatorial means such as data mining and visualization (McDowell and Olson 2008). This independence of materials engineering from product design is inefficient. From a materials perspective, it leads to conservative designs that do not take advantage of the full capabilities of a material (Pollock 2011; Brinson 2011; Anonymous on ICME 2011). Hence, one likely evolutionary breakthrough will be utilizing materials to their fullest by enabling the design engineer to delay specific material choices to later stages of the product-development process. Secondly, revolutionary breakthrough will likely occur by accelerating the materials-design process to facilitate new materials discoveries through computational methods (Anonymous on ICME 2011; NRC 2004a). Another likely trend will be in material designs driven by global challenges such as environmental sustainability. One example of this was demonstrated with the streamlined development of the Ferrium S53 alloy for aircraft landing gears through the DARPA AIM program (Olson 2011; NRC 2004a). In part, the project was driven by a need to remove a toxic, environmentally unfriendly cadmium plating step from the process (Kuehmann, Olson, and Jou 2003). The project was able to achieve removal of this step as well as materials and manufacturing cost reductions over a shorter timeframe than would have occurred using traditional, empirically based approaches (NRC 2008a, 2011). As demonstrated by this example, *other sustainability-driven designs may lead to reductions in the use of environmentally unfriendly materials and processes.*

Supply risks and concomitant price disruptions may also drive materials and product designs. This was the reason for a project initiated in 2002 by GE Global Research and GE energy, which aimed to replace a tantalum-containing superalloy with one that was less vulnerable to shocks in price and supply (NRC 2011). Researchers employed AIM/ICME approaches to substitute tantalum with niobium and other elemental concentrations, ultimately resulting in GTD262, a superior, tantalum-free alloy that was introduced in GE power generation gas turbines in 2006 (NRC 2011). As illustrated by the development of GTD262, *supply-chain risks could lead to the use of ICME for*

facilitating the substitution of critical materials such as rare-earth elements with materials that are more readily available via a domestic or diversified supply chain.

Data

There is a move toward *better handling of data and resources on material properties*. MatWeb, eFunda, and IDEMAT are just a few of the many examples of currently available databases that provide information on material properties as free or inexpensive, Web-based or downloadable resources.⁹ The Calculation of Phase Diagrams (CALPHAD) also deserves mention, for it has come a long way since its start in the 1950s in providing accessible information on thermodynamic properties and empirical data; its capability is the result of sustained efforts by many and enabling factors such as an agreed-on taxonomy that will similarly aid ICME, in general (NRC 2008a). Database activities are constantly expanding the breadth of available information as evidenced by the Materials Atlas, an effort originally supported by the ONR/DARPA “D3D” Digital Structure Consortium, which offers accessibility to three-dimensional microstructural data for a variety of materials.¹⁰

Despite the extensive coverage of materials classes in existing databases, they often lack critically important information such as surface properties, microstructure, and manufacturing history (Senos, Ramalhete, and Aguiar 2010). Thus, one possible advancement in the development of databases is a move toward curated resources that will help fill in key information gaps as well as ensure high standards of data quality. Ultimately, this would result in reliable, previously validated information on any class of materials. Regardless of the shape the databases and repositories take, a breakthrough in information management is likely because it is embedded in much of what we now do (LeSar 2011; NRC 2008a).

In building the necessary databases of materials information, a key first step will be working toward a *unified materials taxonomy*. This is one of the lessons learned from the Human Genome Project, an example of successful international coordination of information that resulted in an extensive, well-researched database of information on human genome sequencing.¹¹ More recently, various bioinformatics databases (e.g., GenBank for genetic sequences and SwissProt for protein sequences) have also emerged through support from the National Center for Biotechnology Information, a division of the National Library of Medicine at the National Institutes of Health (NRC 2008a). In

⁹ Further information and discussion on 87 international materials databases is presented in the work by Senos, Ramalhete, and Aguiar (2010).

¹⁰ The Materials Atlas is currently hosted by Iowa State University at <https://cosmicweb.mse.iastate.edu/wiki/display/home/Materials+Atlas+Home>.

¹¹ More information on the Human Genome Project can be found at the DOE-sponsored website: http://www.ornl.gov/sci/techresources/Human_Genome/home.shtml.

each case, a key take-away was the initial development of a taxonomy that was flexible enough to accommodate future modifications (NRC 2008a).

Another necessary development is the *integration of tools*, including the linking of computational tools and databases for networked collaboration. Such integration would help shift materials design away from the linear paradigm of development and toward a more parallelized process that could in some ways resemble “material war gaming,” that is, simulations of many different design options or trade-offs (Anonymous 1 on Advanced Materials 2011). The end result would be fewer design iterations and prototypes as the fundamental databases and integration reduce the need for associated testing.

There is a *potential for data to be extracted from old sources of information and applied in new ways*. For example, Ph.D. theses could be mined for useful information—including not just text but also graphics—which could then be tagged with relevant metadata for future access (Anonymous 1 on Advanced Materials 2011).¹² Resultantly large data catalogs could be reduced through projects like the Sloan Digital Sky Survey, which helped integrate disparate pieces of data on astronomical objects through automated tools (NRC 2008a).

Technology

CALPHAD software, including DICTRA, Thermo-Calc, and Precipalc has been employed in making thermodynamic predictions regarding multi-component systems and already supports design and AIM qualification in current commercial practice (Olson 2011). Other software codes such as Materials Studio (Accelerys), Gaussian, and LAMMPS (Sandia molecular dynamics code) are useful, yet have a limited suite of capabilities. Moreover, they often require sophisticated scripting for specific applications. One possible advancement is the introduction of Windows-based, user-friendly codes that can be employed by the general workforce, which may not have grown up with understanding the complexities of existing codes (Christensen 2011b).

With respect to hardware, supercomputers are accessible to a limited number of large companies having the financial resources to obtain and maintain them. Even with access to some government supercomputers, small and large companies have issues with exposing proprietary information (Christensen 2011b). *Computing power will inevitably grow*, potentially alleviating some of the current ICME needs for supercomputing power.

Materials modeling in areas such as electron structure and local-density approximation (LDA) has advanced considerably in recent years, but there is still

¹² A more thorough treatment of the frontiers in data mining is provided in recent textbooks such as *Data Mining: Concepts and Techniques* (Han and Kamber 2011) and *Data Mining: Practical Machine Learning Tools and Techniques* (Witten and Frank 2005).

significant room for progress. In the case of LDA, improvements are needed to enable dynamics calculations on the fly, which would eliminate the need for empirical potentials and, in turn, enable more accurate prediction of behavior including defect energies and alloy thermodynamics (LeSar 2011). *Informatics will be essential to harnessing developments in modeling* through its extraction of information and trends (LeSar 2011). Some examples of informatics coupled with LDA simulations and calculations are already employed. One early example is helping in the research of Li-ion battery materials (Ceder 2010). Further breakthroughs in the area of informatics are also needed to extract information from increasingly complex models and simulations (LeSar 2011). Due to the numerous modeling and simulation scales already in use and the many groups that develop them, advancements in informatics may also play a key role in beginning to link across them (LeSar 2011).

Similar to the way finite-element analysis has had a substantial influence on the way people design products, there will *likely be a breakthrough in developing suites of models that become commonplace* (Pollock 2011). The suite of tools will connect, enhance, and even replace what is already in existence, allowing people to start with new materials or dramatically different used materials and still develop a product from start to finish in 1–5 years instead of the 10–30 years required at present. Such capabilities will become an imperative for companies as it provides a strategic advantage to develop materials as fast as design (Pollock 2011).

Trends: Long Term

Most experts hesitated to present potential futures out to 2030 and beyond, but those that offered their opinions focused on improvements in design, technology, and supply chain. The following section summarizes the responses from experts.

Design

Design is an area that is likely to see continued advancements beyond the 10-year time frame already discussed. As certain materials become scarcer or increasingly vulnerable to supply risk, these design constraints will be incorporated into the engineering of products and constituent materials. *Broader societal trends in sustainability will likely lead to greater application of concepts such as materials substitution and recycling, which will be aided by ICME tools.* Moreover, the degrees of freedom allowed in designing materials will continue to grow, thus necessitating the use of ICME tools to better assess the trade-offs of various material choices (LeSar 2011). This will also lead to the *blurring of the line between mechanical and materials design*. Component design and manufacturing will be done using almost entirely computationally based methods as disciplines begin to speak the same language (Anonymous on ICME 2011).

In the past, there has been a lot of discussion on using ICME for designing products for strength or other material properties, but one often overlooked area is prognosis, or lifetime prediction. Combining ICME with nondestructive evaluation will greatly enhance the ability to predict a materials lifetime. ICME will provide more robust designs by more accurately predicting lifetime constraints. Currently, product lifetimes are extremely conservative, especially in the case of defense-critical materials, where probabilistic or other primitive models are used to predict a component or product's time to failure. This ultimately leads to wasting huge amounts of time and throwing away resources simply because parts are replaced earlier than is necessary (LeSar 2011).

In 20 years there will likely be a shift in the way materials specifications or design codes are applied. Unlike today, most work will be left to computation, which will allow increasingly complex components and systems to be designed with relative ease. *All the data will be available to the designer, resulting in unsurpassed freedom of design.* This is in contrast to today where we use specifications and materials that are constant with one set of properties (Anonymous on ICME 2011). In other words, materials design, processing, and product engineering will become coordinated as computational abilities continue to improve.

Materials discoveries will likely be catalyzed once ICME tools are available. Creativity will be sparked, and it will drive the development of new suppliers that make things with new techniques such as additive manufacturing, but it will require enough confidence in the tools that firms are willing to completely change their design systems. (Pollock 2011)

Technology

Supercomputing power will inevitably increase over the next 20 years. Thus, one likely advancement is the ability to perform quantum-level models with thousands of atoms but on local computers that do not require the computing force of today's supercomputers (Christensen 2011b).

There is interest in new methods using additive-printing technology for direct writing of materials; this essentially demands the use of ICME to optimize the materials and processes involved (LeSar 2011).

Supply Chain

The deployment of ICME into industrial applications requires numerous organizations from academia and industry to provide and maintain tools that cross a variety of disciplines (Furrer and Schirra 2011; Pollock 2011). *While the supply chain may ultimately take on a number of different forms, its establishment will require a better understanding of the relationships among sectors, their requirements, and the roles of*

individual suppliers (Furrer and Schirra 2011). It is clear that individual companies will not have all the people and resources they need to fully take advantage of ICME. What the supply chain ultimately looks like will depend on whether there is a large, coordinated effort that will benefit from government investment or whether it is accomplished through small grants to universities and other organizations (Pollock 2011).

Barriers

Despite recent advancement of ICME concepts, a variety of technical, cultural, and other factors persist as barriers to progress in the field. Major efforts will be needed to overcome some of these challenges, which require both evolutionary and revolutionary advances across many disciplines.

Technology

With respect to technical challenges, *a formidable issue is the complicated behavior of materials that involve complex physical phenomena spanning widely different length and time scales*. Capturing this complex behavior in models is difficult, and there is currently inadequate support for wide use of ICME due to lacking theoretical knowledge. Empirical models must advance to fill in appropriate gaps, but significant work is needed in the area of modeling (NRC 2008a). One expert noted that fundamental scientific discoveries, rather than practical ones, would remain as barriers in 20 years (Christensen 2011b).

One of the key issues with modeling is characterizing uncertainty. Sources of uncertainty include natural variability in materials, incomplete knowledge of model parameters, and poor model structures due to insufficient data. Accurate characterizations of uncertainty must be propagated through various length and time scales to enable successful multiscale models (Samaras, Victoria, and Hoffelner 2009; Isukapalli, Roy, and Georgopoulos 1998).

With respect to databases, *unifying taxonomies are needed, along with informatics for information extraction*. Large volumes of data are already in existence, but information is scattered, dispersed, or difficult to access. NSF is attempting to lessen the problem by requiring data-management plans for all new proposals, but more integrated plans for database management are still lacking (Freiman, Madsen, and Rumble 2011). Information has to be accessible by the members of the materials R&D, design, and manufacturing communities, and it must be navigable by users with varying ranges of expertise.

Managing and curating data will be one of the biggest barriers (Pollock 2011; Brinson 2011). Questions of data provenance and stewardship remain, along with the sources of funding and human resources to maintain the necessary databases and

cyberinfrastructure. They are unlikely to be developed organically, and some effort will be required in convincing researchers to share information (Brinson 2011).

Moving forward, *integration tools will be a necessary component of the ICME framework*. Virtual libraries of material property data are needed, but they must be properly linked to be usable in the variety of models employed by ICME. Proper networking tools are also required to facilitate the necessary collaboration between the different disciplines involved and allow for true optimization of materials, products, and processes.

Rapid experimentation and three-dimensional characterization techniques are needed to enable rapid evaluation and screening via information such as phase diagrams (Zhao 2006). One example of a nascent technique is three-dimensional tomography, which was at the heart of the recent ONR/DARPA “D3D” Digital Structure Consortium, where atom-probe tomography was coupled with multiscale modeling to achieve alloys with maximum strength (McDowell and Olson 2008). A number of other characterization tools are beginning to emerge, as described in detail by Robertson et al. (2011). Such tools need to be further refined and their results communicated through predetermined protocols to enable access to the large amounts of data that they will produce (NRC 2008b).

Other Factors

Other barriers described in this section are cultural barriers such as education, intellectual property issues, and funding difficulties. Also detailed are challenges related to export controls, regulatory issues, standards, and supply-chain developments.

One of the primary cultural barriers to ICME is education. There is a need for people who are skilled at developing aspects of ICME (e.g., creating models or building cyberinfrastructure), as well as those who can employ the approaches (e.g., running simulations or assessing tradeoffs) (Christensen 2011b). Currently, the proficiency of the workforce—including those with undergraduate and graduate degrees—is limited (LeSar 2011).

Another barrier is the ability to accurately *verify and validate models to the fidelity acceptable to regulatory agencies*. Specifically, the role of regulatory agencies in the verification and validation process remains unclear. Nonetheless, there is at least one example of existing regulatory influence in embedded design certification with DARWIN, an FAA-sponsored probabilistic damage-tolerance software package that incorporates safety information from the FAA (Wu, Enright, and Millwater 2002).

The insertion of ICME concepts into industrial processes will require new approaches, including in some cases the use of a non-constant materials definition (Anonymous on ICME 2011). This shift from a singular material choice to a

parametrically based material definition will provide flexibility in design through the development process but it requires cultural and organizational changes, which includes decision-making across disciplines and appropriate training of individuals to use new software tools (NRC 2004b).

In viewing recent examples of ICME approaches at companies like Ford and Pratt & Whitney, it is clear that *employing these methods is expensive* (NRC 2008a). Thus, another crucial barrier will be settling intellectual property issues that allow companies to protect their investments as well as sensitive work such as what is perform for the Department of Defense. In this system, it will also be important to ensure an infrastructure where more than just a few companies benefit. While many of the models in academia should remain open and available to everyone, all models need support, testing, and validation, which could remain as proprietary functions that involve teams of people from academia, government, and industry (Pollock 2011). Overall, a balance must be achieved to allow for transparency without sacrificing proprietary advancements that motivate companies to participate in ICME (NRC 2008a).

Funding was commonly cited by experts as a barrier to entry. Even software packages are expensive, sometimes requiring upwards of half a million dollars annually to maintain site-wide user licenses (Christensen 2011b). Moreover, state-of-the-art computers to run the software can require investments on the order of \$1 million every couple of years (Christensen 2011b).

Another barrier associated with money is the *inability of funding agencies to support integrated efforts of the right groups of researchers from the various disciplines needed to make ICME successful* (LeSar 2011). Funding programs are often narrowly limited to material classes or applications, which inhibits interdisciplinary collaborations (McDowell 2011). Time horizons are also limited with most money provided by funding agencies not occurring on a cycle long enough to provide the needed foundational support for ICME. A recent study suggested that funding cycles may need to be as high as 5 years or more to support the needed multidisciplinary teams and to develop key simulation codes that would run on U.S. computing platforms (Glotzer et al. 2009). This is out of sync with the typical 1-year investment cycle and most product R&D cycles (NRC 2008a).

Some experts were *concerned about future limitations that may be imposed by export controls or International Traffic in Arms Regulations (ITAR) restrictions*. In particular, there was concern that restrictions on U.S. universities could lead to non-U.S. institutions achieving gains (Anonymous on ICME 2011). In the more near term, there are particular issues in using offshore commercial software providers such as ProCAST, iSight, and Abaqus. Specifically, ITAR or export-controlled materials and processes may require tailored software modules, which complicates the exchange of controlled data (Cowles and Backman 2010). In addition, some software developers now employ

business models where the developer possesses ownership of future software derivatives (Cowles and Backman 2010).

There are still some *challenges in forming the appropriate linkages in the supply chain to advance ICME*. Industry now understands the utility of modeling and simulation tools, but they are not user friendly to the non-academic (Pollock 2011). Several small companies, including Scientific Forming Technologies Corporation (SFTC) and Computherm LLC are working with the aid of Small Business Innovation Research or Small Business Technology Transfer grants to better integrate code and move it beyond the laboratory (NRC 2004a, 2008b). Despite these small business examples, there is a *“missing layer” of small companies to help commercialize code written in academia and move it to big industry* (Pollock 2011).

Note that most experts agreed that *computational power will not be a limitation moving forward* (Pollock 2011; Christensen 2011b).

Global Development

The United States is currently among the leading countries in efforts to develop ICME tools; however, other countries, especially those in the European Union, are also making significant investments in this area (Allison 2011; Pollock 2011). Within the EU, Germany and the United Kingdom are the dominant countries in ICME concepts, especially relating to automotive and defense applications (Anonymous on ICME 2011; Pollock 2011), with Sweden also making significant contributions (Pollock 2011). France also has ongoing work in the direction that meets its needs in nuclear and defense applications (Pollock 2011). Note that research in ICME in the EU is often centered on the concept of “through-process modeling” (Allison 2011; LeSar 2011; Pollock 2011). For example, one of the early European-funded examples included a triumvirate of projects named Vir[CAST], Vir[FAB], and Vir[FORM] that were initiated in 2000. The €17 million project coordinated among universities, research institutes, and major aluminum companies ultimately resulted in the establishment of a series of modeling tools that can simulate the entire processing chain for aluminum alloys (Cheng et al. 2007).

One indication of China’s growing interest in ICME occurred in 2009, when the Chinese Academy of Sciences selected the 2008 National Academies report on ICME as one of a few priority reports to be translated into Chinese (Allison 2011). Whereas China’s computational capabilities have been increasing along with the number of ICME-related publications (LeSar 2011), their potential remains unclear (Pollock 2011). China is also the site of one of three proposed university ICME centers, with the United Kingdom and United States likely to host others (Allison 2010).

One expert noted that market forces may begin to prompt other countries, such as Singapore and South Korea, to begin to explore ICME for consumer electronics (Anonymous 1 on Advanced Materials 2011). There is also interest in ICME, along with computational materials science strengths, in Japan (Pollock 2011). Australia also has emerging work in ICME especially on lightweighting and three-dimensional aspects (Pollock 2011).

Appendix H.

Additive Manufacturing Processes

The term “additive manufacturing” describes several techniques in use since the mid-1980s to build solid parts by adding materials in layers. Although other terms are in usage, the field is slowly coalescing around the term “additive manufacturing” because it concisely distinguishes it from more traditional “subtractive” processes that remove material from solid blocks with various tools or techniques. Additive manufacturing creates free-form objects using a bottom-up approach that employs computer-aided design (CAD) programs and machines that now come in many sizes, use many processes, and have varying levels of precision (Beaman et al. 1997; Venuvinod and Ma 2004; Wohlers 2011b).

The growth of additive manufacturing represents a shift in the way several types of goods are conceived of, made, delivered, and used. Consequently, there remains a potential for significant impacts to the global manufacturing sector—including changes to intellectual-property rights and product-liability claims—with the possibility of several types of new industrial and consumer goods in the next 20 years. This appendix explores current trends in additive manufacturing, potential advancements, and the effects that this technology could have on global manufacturing and product development.

Rationale for Selection Based on Criteria

In terms of the five trends discussed in Chapter 3, additive manufacturing techniques are most germane to those on following broader trends in manufacturing (3.A.1.a) and enabling platform technology (3.A.1.b). To the extent that mass customization is a broader trend in the manufacturing sector, additive manufacturing techniques represent one of the only economical methods to meet the corresponding requirements for it—these techniques also represent an enabling technology since they permit wholly new types of design without the imposed limitations of machining.

Additive manufacturing also relates to the other three criteria (3.A.1.c–3.A.1.e), though somewhat less so. In terms of criticality to national security, additive manufacturing techniques are not substantially used in defense applications at present. However, they have the potential to play a large role in future design of defense applications such as aerospace, which has demands for continuous lightweighting of components. Several additive manufacturing companies, including Solidica and Arcam, are already working with military researchers. Many of the large defense aerospace

contractors, including Lockheed Martin, Northrop Grumman, and Boeing, are highly interested in additive technology (Frazier 2011; Slattery 2011). Additive manufacturing also has the potential to produce spare parts on demand and on location, thus saving time and inventory costs (see sidebar “Additive manufacturing excels when parts are designed to be made together” in Chapter 3.D.1).

With respect to global investments, additive manufacturing still represents a fairly small industry, with around \$1.2 billion in sales of system, materials, and services in 2010. However, the industry is rapidly expanding and expected to continue to do so—the average compound growth rate from 1989 to 2010 is above 26% (Wohlers 2011b). Finally, in terms of other factors, issues such as cybersecurity and intellectual property also play a role in the development and spread of additive manufacturing techniques. See the section of this appendix titled “Barriers to Adoption.”

History and Definition of Additive Manufacturing

The history of additive manufacturing begins with the field of rapid prototyping (RP). The original additive manufacturing processes first gained a foothold in companies that need to quickly create a physical prototype, allowing clients to visually inspect product designs. The first machines for RP were commercialized in 1987 by 3D Systems using a process called stereolithography to produce plastic parts (Hopkinson 2010). New techniques using deposition and laser-based processes were commercialized in the early 1990s. Around the same time, research at MIT eventually led to the commercialization of machines using inkjet printing or three-dimensional printing (Wohlers 2011b). As time progressed, these processes were refined; other processes were created; and new materials, including metals and ceramics, were introduced. Eventually, these processes matured to a point where the quality of their output (measured by surface finish and mechanical properties) was good enough to produce final goods, not just prototypes. Today, while the majority of additive manufacturing techniques are still used for rapid product development and prototyping, the techniques are increasingly used to create final products. Such “direct part production” is believed by many to represent the future of additive-manufacturing technology.

Through its short history, additive manufacturing techniques have been described by different terms with slightly different meanings:

- Automated fabrication
- Solid free-form fabrication
- Direct digital manufacturing
- Stereolithography
- three-dimensional printing

- Rapid prototyping

A recently convened technical committee at standards body ASTM International (ASTM F42) agreed that the standard terminology to refer to the entire field should be additive manufacturing, and this is the term utilized here (Gibson, Rosen, and Stucker 2010).

Current Areas of Application

Current and future application areas that use additive manufacturing techniques for direct part production depend on a few limiting criteria:

- *Small production runs*—Additive manufacturing techniques and materials are still more expensive than traditional counterparts for large production runs, and thus they are most competitive where their quick production time and flexibility are needed. This includes customized parts and runs that are intended to produce very few parts.
- *Small part size*—Due to the limitations in size of many current-generation machines as well as their low production speed, additive manufacturing techniques will compete mostly in the market for smaller parts and components (typical build sizes $\sim 1 \text{ ft}^3$, (Wohlers)), at least in the near term.
- *High value products*—Due to speed and the high cost of materials and processes, high-value markets will be better suited for additive manufacturing.
- *Products with complex (internal) geometry*—Because creating some complex internal geometries is not possible using many traditional methods, additive manufacturing can easily compete where complex geometry is desirable.

Given these criteria, there are a relatively small number of application areas where additive manufacturing is beginning to compete with traditional techniques outside of its historical role in the rapid creation of prototypes. In addition, several areas are beginning to look promising for large-scale use of additive techniques in the creation of final parts, that is, direct part production. The remainder of this appendix focuses on direct part production, a trend that has long been viewed as the eventual potential of the technology (Venuvinod and Ma 2004; Beaman et al. 2004; Wohlers 2011b; Beaman et al. 1997).

Wohlers (2011b) conducts an industry survey each year of additive manufacturing system manufacturers and service providers to determine current areas of application. The most recent survey concluded that consumer products and electronics; transportation, industrial machinery, and medical and dental applications together represent around 75% of the current additive manufacturing market. A 2009 roadmap for the technology concluded with a similar list of potential areas where additive manufacturing could compete: aerospace and military, automotive, electronics, biomedical and dentistry, and

consumer products (Bourell, Leu, and Rosen 2009). These current users are described in more detail in the sections that follow.

Industrial Machinery and Rapid Tooling

Traditionally, creating tools and molds for manufacturing has been a costly and time-intensive process. Additive manufacturing can be used to reduce or eliminate the costs associated with tooling, which was one of its first non-prototype applications. Additive manufacturing can be used in several ways for rapid tooling: to develop prototype castings for testing a design, to allow faster delivery of production castings while wax tooling is still being produced, and to produce low-volume items where new tools may be cost prohibitive (Wohlers 2011b). Thus, even in industries where additive manufacturing cannot compete to produce final parts due to economies of scale, it can still provide molds and tools. Further, in some cases additive-made molds can perform better than traditional molds because they significantly reduce cooling times through more efficient cooling channels (Wohlers 2011b). In many cases it is difficult to predict the size of production runs given potential design changes and market uncertainty. Thus, being able to easily change design can be important. Additive techniques are a growing part of the jewelry industry; jewelers use them to produce items exactly to customer specification without relying on expensive pattern-making.

Medical Applications

Additive techniques are growing quickly in many aspects of medicine, including producing surgical models, medical instruments, dental implants, and recently surgical implants. These applications take advantage of the easy customization allowed by additive techniques and decreasing costs of medical imaging such as computed tomography.

Aerospace and Motor Vehicles

Additive manufacturing is now beginning to have an impact on the aerospace and motor vehicle markets because of more low-production runs, more high-value goods (particularly in aerospace), and the desirability of lightweight parts. Generally, parts currently being made by additive techniques are not safety-critical members because certifications and materials properties are either unknown or distrusted by designers. Examples in aerospace include air ducts, which often have complex geometries in airplanes, and audio system and headrest parts in automobiles (Wohlers 2011b). Many companies and organizations are also conducting extensive research on additive manufacturing's potential for transportation equipment. NASA and General Electric are working on turbine blades and parts, and Boeing and Northrop Grumman are examining the production of polymer components (Stucker 2011). The European Aeronautic

Defense and Space Company (EADS) has been working with additive manufacturing as well, recently announcing the use of a nylon additive process to produce a bicycle called the “AirBike,” shown in Figure H-1.



Source: Photograph used with permission from EADS.

Figure H-1. EADS AirBike.

Consumer Goods

Consumer applications have also started to take advantage of the complex geometries and customization that additive manufacturing offers. Several new types of businesses have been enabled by additive manufacturing, including online businesses that will fabricate nearly any three-dimensional design a consumer desires. One commonly cited example is called FigurePrints, an online company specializing in creating replicas of digital avatars from the video game World of Warcraft and the Xbox Live video game system. Other types of businesses allow consumers to either wholly design their own goods or customize existing designs with names, alternate sizes, or other unique features. For example, the online company Shapeways brings together designers and consumers, allowing individual consumers to request design changes and personalization of items before they are manufactured by Shapeways and shipped to the consumer (Lipson and Kurman 2011). The complex geometries that additive manufacturing allows have already allowed for new artistic design for everyday goods such as lamps, trophies, and statues. (Wohlers 2011b).

Current Processes

All current additive manufacturing approaches (see sidebar “Additive Manufacturing Processes—Examples”) use a layering approach, such that the fabricated part is an approximation of the original computerized design, with the approximation growing closer to the design as the layer thickness decreases. The thickness of the layers and how they are bonded determine the material and mechanical properties, as well as some important economic indicators: the time and expense required to make the part and the post-processing necessary (Gibson, Rosen, and Stucker 2010).

Typically, additive manufacturing processes are classified in one of two ways: by the material or physical process used in production of the part. These are not necessarily mutually exclusive classifications—some processes employ a limited set of materials. For example, stereolithography uses only plastics. In terms of materials, the large majority of processes produce parts using either plastics or metals (though some ceramics are also in limited use). Some examples of natural materials (e.g., living tissue, starch) have also been demonstrated (Bourell, Leu, and Rosen 2009).

Production and Usage of Additive Manufacturing Machines by Country

Given the high growth rates in, and growing levels of, global investment, it is important to examine investment and capacity by country. The industry is expected to become more competitive over time as initial patents for the founding technologies begin to expire (Bourell 2011).

One crucial trend in the industry over the past decade has been a bifurcation between manufacturers and processes focused on the low-cost consumer or prototyping markets and those focused on the high-cost machines used to directly fabricate final parts (Bourell, Leu, and Rosen 2009). Machines designed for the consumer market now cost as low as \$1000, although they have limited materials choices and generally produce fairly poor materials and surface properties; on the other hand, high-end direct metal machines can cost \$500,000 and produce high-quality parts from several types of metal with very good properties. (An example of this bifurcation is the company Bits from Bytes, which sold 17% of all machines worldwide in its first year of production, after which it was acquired by industrial machine producer 3D Systems. Because of the growth of personal scale systems, total additive manufacturing machines sales value went down for first time ever from 2008 to 2009, but the number of machines sold rose by 20% (Lipson and Kurman 2011).

Additive Manufacturing Processes—Examples

The most common additive manufacturing processes are listed below, along with details regarding their main defining characteristics (Hopkinson 2010; Bourell, Leu, and Rosen 2009; Beaman et al. 2004):

- **Powder bed (laser) sintering**—Laser sintering fuses together powder from a bed. Originally, laser sintering could produce polymer as well as metallic and ceramic parts (using each type of powder), with binders needed in the case of metal or ceramic powders. Recently, more powerful lasers have been used to directly sinter metal and ceramic without the use of binders (Hopkinson 2010).
 - **Advantage:** Parts made from laser sintering tend to have good material properties and can create relatively fine features down to 0.1 mm (Christensen 2011a).
- **Fused deposition modeling (FDM)**—This process uses hot nozzles to extrude polymeric material into position, using one nozzle to extrude support material and a second to extrude the part.
 - **Advantage:** These machines are among the least expensive.
 - **Disadvantage:** The machines have relatively weak parts due to poor interlayer bonding. Materials also tend to be fairly expensive (Hopkinson 2010).
- **Stereolithography**—This process makes use of photo-curable plastic resins that are treated by UV laser to become solid or gel-like and is most often used for prototyping (Hopkinson 2010).
 - **Advantage:** This process is relatively more accurate than other methods and is able to create relatively fine feature sizes.
 - **Disadvantage:** The photo-curable resins have limited long-term stability due to continued curing and warping throughout the part's lifetime. Thus, stereolithography processes are most often used for prototyping (Hopkinson 2010).
- **Inkjet deposition (three-dimensional printing)**—This process uses an inkjet like those found in two-dimensional printers. It works by depositing a binder on a powder bed that joins the powder in each layer without the use of lasers.
 - **Advantage:** In the future, different inkjet heads may also facilitate multiple materials (Cormier 2011).
 - **Disadvantage:** Without post-processing, material properties are considerably weaker using this process compared with those made by laser sintering (Beaman et al. 2004, Hopkinson 2010).
- **Electron beam (e-beam) melting**—This is a process that uses an electron beam in place of a laser to directly melt metal powder into parts. (Arcam, a Swedish manufacturer, has pioneered the use of electron beam melting.)
 - **Advantage:** The process is many times faster than comparative laser-sintering processes, as well as more energy efficient (Wohlers 2011b).
 - **Disadvantage:** These machines are expensive, and while surface finish properties are steadily improving, they are still of lower quality than laser-based metal processes (Cormier 2011).
- **Ultrasonic consolidation (UC)**—UC is one of the newest additive manufacturing technologies, patented by an American company called Solidica and in development by Solidica and the Edison Welding Institute (Slattery 2011). This process uses metal foils held together under pressure, combined with ultrasonic vibrations that create a weld between layers of foil, which are then machined to the desired shape.
 - **Advantage:** It can weld together multiple metals (Ram et al. 2007).

As the initial developer of many of the additive processes, the United States is in a strong position to continue as an industry leader in many areas of additive manufacturing, including low- to mid-priced machine manufacture and adoption. In terms of total installed base, the North American region leads with 43% of machines, followed by 30% in Europe, 23% in Asia-Pacific, and the remainder in other areas (Wohlers 2011b). Leading U.S. companies include Stratasys and 3D Systems, both major players in the global market for plastics additive manufacturing who have made acquisitions in recent years after substantial growth. Stratasys, which mainly uses FDM processes, recently announced a partnership with Hewlett-Packard to produce three-dimensional printers, a move some see representing a watershed moment for the technology due to the capital and brand of HP (Wohlers 2011b). 3D Systems has made many acquisitions recently among both equipment manufacturers and service providers, often known as service bureaus in the industry (Wohlers 2011b).

Europe used to be primarily a customer of additive manufacturing systems from the United States, and while several U.S. manufacturers are still successful in the European market, *several European manufacturers are now competing* well in many market segments, particularly among metals systems. Many experts suggested that European companies represent the state of the art in metals additive manufacturing technology, including Arcam (Sweden) and EOS (Germany), as well as several others (Frank 2011; Wicker 2011). While each individual company may be smaller than U.S. companies, together they have a lead in the direct metal manufacturing segment of the market. Europe also is a leader in direct metal research. In Germany, The Fraunhofer Institute is a leader in laser technology and has done significant research on laser-based additive processes; the Katholieke Universiteit Leuven in Belgium is a world leader in direct metal additive manufacturing; and Loughborough University in the United Kingdom is also widely recognized for its expertise (Wohlers 2011b; Bourell 2011).

Roughly one quarter of all additive manufacturing machines are estimated to be installed in Asia, with Japan accounting for almost half and China representing slightly more than one quarter (Wohlers 2011b). While Japan was an early adopter of additive technology, its companies are now struggling and have been relatively unable to sell machines to manufacturers outside of Japan. The situation is similar in China—few Chinese machines are sold outside of the country—however, the Chinese industry is still growing from a nascent beginning just a few years ago. A large number of Chinese companies now offer additive manufacturing services, mainly for design and prototyping rather than part production. This trend is notable as an example of how earlier stages of product value chains are moving to Asia. Many of the Chinese companies started at universities due to import restrictions and the high prices of the technology. There is some growth in Asia outside of Japan and China, including Taiwan and Australia, but as

with China, the growth is mainly in use rather than in innovation and development (Wohlers 2011b).

Finally, *Israel has emerged as a global player mostly due to a single company, Objet Geometries* (Wohlers 2011b). Objet utilizes three-dimensional printing inkjet technology and manufactures several low- to mid-priced systems, some of which fit on a desktop. One of the major selling points of Objet's technology is the ability to print in multiple polymeric materials displaying different material properties. Since its inception, Objet has sold nearly as many machines as all the European companies combined (Wohlers 2011b).

Trends: Near Term

The following sections discuss observations on additive manufacturing's future over the next 20 years, as well as some of the barriers that are preventing advancement of additive manufacturing as a manufacturing process for industrial parts or direct consumer production (Bourell, Leu, and Rosen 2009; NCMS 1998).

Since at least the late 1990s, industry experts have anticipated a divergence between the markets that will make use of additive manufacturing. Some companies are marketing extremely low-cost, polymer-based systems with relatively poor material property output for the consumer and hobbyist market, while others are focusing on very high cost systems meant for direct part production (NCMS 1998). A 2009 industry roadmap recognized that this divergent trend was already occurring and predicted future trifurcation between low-cost consumer systems, high-end direct part systems, and mid-range systems for rapid prototyping (Bourell, Leu, and Rosen 2009). Thus, we follow this categorization here and separately discuss likely trends for the technology itself, other related trends such as standardization, and three markets likely to make extensive use of additive manufacturing techniques over the next 20 years: medical, aerospace, and consumer markets.

Technology Trends

In the next decade, several important trends will continue to improve additive technologies and make them more competitive with traditional manufacturing approaches.

Process Improvements—The field of additive manufacturing has already produced several different processes. In the coming years, processes will continue to improve, with some advancing more quickly than others. In the case of plastics, FDM, stereolithography, and laser sintering are the current front-runners from a materials strength standpoint and will continue to improve (Christensen 2011a). Inkjet technologies also likely have a bright future based on their high throughput and ability to deposit multiple different kinds

of materials (Cormier 2011). In terms of metals, laser and e-beam technologies will continue to produce smaller feature sizes and smoother finishes (Cormier 2011).

While each technology continues to improve, many experts believe that future machines will increasingly utilize hybrid technologies that take advantage of the strengths of several types of additive and subtractive processes (Rosen 2011). Combining multiple additive processes for internal geometry and subtractive processes for better surface and material properties could produce a new generation of digital manufacturing machines with capabilities far exceeding what is possible today (Frank 2011). One other appealing alternative is the automatic insertion of prefabricated components, such that additive processes could be combined with circuitry to create electromechanical systems (Bourell, Leu, and Rosen 2009).

Speed—The coming years will see tremendous focus by machine manufacturers on increasing build speed through increased deposition rates. This is particularly true for powder-based processes, which are currently very slow compared with traditional manufacturing approaches. The key will be the trade-off between feature size and speed, as one must typically be sacrificed for the other (Cormier 2011). There are several alternatives to increase build speed. One method would create faster continuous-flow systems by moving from point processing to line, mask, or volume-based processing (Bourell, Leu, and Rosen 2009). An alternative approach already occurring is parallelization—using multiple lasers, e-beams, or melt pools simultaneously to build (Rosen 2011). While there are challenges from a control standpoint to achieving mass parallelization, the advantages are large enough that they are likely to be overcome.

Quality Control—Machines will begin to increase quality control and produce parts with higher repeatability. Material issues, including thermal distortion between build layers and gas bubble inclusions, currently hamper the quality of output (Wohlers 2011b; Cormier 2011). Attention to these issues could lead to breakthroughs in the quality of additive-produced parts without the reliance on expensive post-processing techniques. But these breakthroughs will require the ability to sense material problems while they are occurring via closed-loop feedback systems. Many experts believe such systems will be widely in place in additive machines in the coming decade (Hazelrigg 2011; Leu 2011; Wicker 2011). New open architectures will allow more routine quality testing as well as research into the

Technology Trends in Additive Manufacturing

- **Process Improvements**—Future machines will increasingly utilize hybrid technologies that take advantage of the strengths of several types of additive and subtractive processes
- **Speed**—The key will be the trade-off between feature size and speed, as one must typically be sacrificed for the other.
- **Quality Control**—Machines will begin to increase quality control and produce parts with higher repeatability.
- **Materials**—Innovations may allow a broader material coverage by additive processes, expanding the current set of materials to include new polymers and potentially even biological materials.

basic science of thermal-distortion-layer issues (Bourell, Leu, and Rosen 2009). Some material properties could also be solved by the integration of emerging processes such as ultrasonic consolidation using foils or cold-spray technologies that mechanically join powders (Cormier 2011).

Materials—As process improvements occur, there will be simultaneous attention given to the materials utilized in additive processes. Improvements will be achieved in single materials for additive processes, as well as new combinations of materials. New innovations may allow a broader material coverage by additive processes, expanding the current set of materials to include new polymers and potentially even biological materials (Leu 2011). Some materials may be designed specifically for additive manufacturing methods. At present, many plastics are designed for specific temperatures and processing environments that may not be relevant to certain additive processes (Kinsella 2011). Simultaneously, more competition among materials providers should reduce the cost of materials for additive manufacturing (Wohlers 2011b). Innovations in machine and materials design could also allow powder recycling, further reducing materials costs (Cormier 2011).

There is also a large move toward multiple material machines, along with the requisite controls and software needed to simultaneously manufacture with heterogeneous materials. A particularly high-value application for additive manufacturing could be in functionally graded materials, where geometries or materials are graded through the component volume to provide additional functionality (Leu 2011; Bourell, Leu, and Rosen 2009).

Standardization

As these technological improvements are being made, significant effort will take place in standardizing specifications for products made by additive processes. Currently, the same digital design has a substantial variation in material and surface properties depending on the machine it is built with, the operator using the machine, and other local environmental conditions. A recently formed technical committee at standards body ASTM International (F42) is working to create specifications for different materials and processes so that buyers and sellers can easily communicate the expected outputs from additive manufacturing (Bourell 2011).

New Design Concepts

As additive processes begin to gain acceptance, there will be potential to utilize new designs and concepts to take advantage of them. This will be particularly true in aerospace and motor vehicles design, where additive manufacturing can facilitate lightweighting, although this will require more information on materials properties, particularly under stress (Kinsella 2011).

There will be challenges to achieving these new designs, notably in the education of designers and the capabilities of CAD software. Current CAD has problems with complex geometry, parametric boundaries, complex materials, and tying geometry to properties (Rosen 2011). New software providers will begin offering CAD solutions, particularly with respect to the growing consumer design market. This new generation of consumer CAD will be significantly simpler and more intuitive for non-specialists. An example is Google's free three-dimensional design tool called SketchUp (Lipson 2011).

Markets Where Additive Manufacturing Will Have an Impact

Advances in technology, materials, and design capabilities will likely spur additive manufacturing to new levels of penetration in many markets over the next 10 years. Again, the use of additive manufacturing for rapid prototyping and rapid product development will certainly continue. New markets that can take advantage of the unique capabilities of additive manufacturing will be brought into the fold as new levels of investment outside of current venture and entrepreneur capital occur (Stucker 2011). Previous roadmaps have suggested that aerospace, automotive, medical, and consumer products will drive the future of additive manufacturing, with help from smaller industries like dentistry and jewelry and collectibles (Bourell, Leu, and Rosen 2009). Experts interviewed for this study agreed that these markets would be important and each is discussed in the sections that follow.

Aerospace

For several years, the aerospace industry has maintained an interest in additive manufacturing because of its generally low production runs and its ability to fabricate parts of complex geometry, which aid fuel efficiency. Additive manufacturing has potential to gain a foothold in the industry with either original equipment manufacturers (OEMs) or spare parts producers. OEMs are currently thinking about design with additive manufacturing in mind, such as in cellular lattice structures that are impossible to produce by conventional techniques but can lead to lighter aircraft with increased fuel efficiency (Frazier 2011). New tools that optimize topology are also beginning to allow designers to meet their constraints with minimum volume material (Wohlers 2011b). Everything from turbine blades to UAV wings could be redesigned using more efficient geometries (Wicker 2011).

Major OEMs like Airbus, Northrop Grumman, and others have all identified parts that could be manufactured by additive techniques (Wohlers 2011b). Lockheed Martin and Northrop Grumman are pursuing additive manufacturing technologies for large parts that they are hoping to introduce on the Joint Strike Fighter (Frazier 2011). Boeing has worked on additive manufacturing since 1997. It is examining the potential for e-beam melting, which has a high deposition rate and avoids the problem of argon entrapment

(Slattery 2011). In the coming decade, Boeing will likely be using additive manufacturing for components on military aircraft but not on commercial aircraft because production rates are not fast enough (Slattery 2011).

Medical

Medical applications of additive manufacturing are also expected to increase considerably in the coming decade, for two main reasons: the need for complex geometries in implants and tissue scaffolds and a desire for mass customization for individual bodies. Current medical tool uses of additive manufacturing are in their infancy but can be classified into two broad categories: the use of traditional materials for structural applications like implants or prosthetics and the printing of actual biological material, also known as biofabrication.

Medical applications of additive manufacturing using traditional materials include producing surgical models, nonbiological implants, tissue scaffolds, and surgical tools. A physical model produced from a medical scans such as an MRI, surgical models help plan patient-specific implants and prosthesis and assist in surgical planning and rehearsal (Bourell, Leu, and Rosen 2009). They are growing in popularity because they can decrease time in surgery, reduce associated costs, and lead to increased success rates (Christensen 2011a).

Surgical implants and tissue scaffolds are widely seen as a large future market for additive manufacturing (Hazelrigg 2011; Wohlers 2011b; Wicker 2011), although the economics of producing customized implants or scaffolds for each patient will depend on the future of technology, regulation, and the type of implant. A few companies in Europe have already made thousands of titanium hip implants using the Arcam EBM (electron beam melting) process. However, these implants were not approved by the FDA for sale in the United States until very recently (Wohlers 2011b). Both implants and scaffolds take advantage of complex porous geometries necessary to attach bone or other tissue to nonbiological material.

One expert in the field believed that additive manufacturing is unlikely to be competitive for producing the most common implants like hips and knees because the cost of the machine is currently too high. The top-four companies controlling most of the market for these implants have not been involved with additive manufacturing for this reason (Christensen 2011a). However, a potential middle road between additive-made custom implants and the current mass-produced implants is the use of custom surgical guides made for every patient. These guides consist of plastic pieces that help surgeons place an implant in the patient. They can decrease surgical time and increase the probability of long-term implant success (Christensen 2011a).

There is also a recent movement toward using additive techniques to fabricate or print actual biological material, sometimes called biofabrication or organ printing. In the future, printed organs or tissues could have several potential uses, such as for drug testing, biosensing, drug delivery, and organ implants (Bourell, Leu, and Rosen 2009). In 5 years, it is likely that three-dimensional cell models for *in vitro* studies should be available, but this is dependent on the development of new biomaterials capable of being printed. Printing tissues themselves may occur in 10 years, though printing whole organs is unlikely to occur within the 10 year time frame (Bourell, Leu, and Rosen 2009; Sun 2011).

Consumer

While additive manufacturing is beginning to have an impact in industrial markets, the price will continue to drop and market penetration will continue to rise for small-scale personal fabrication machines. A low-cost version under \$500 may arrive in 5 to 10 years (Bourell 2011; Rosen 2011). Currently, several companies offer three-dimensional printers under \$2000 (Wohlers 2011b) and home-use kits to create an entry-level fabrication machine for under \$1000 (Lipson and Kurman 2011). Although most of the companies producing these low-end machines are not yet major players in the market, there are significant investments and many patents, all of which will affect the market in 5 to 10 years (Bourell 2011). Such machines will likely be limited to plastics due to cost and safety issues, and experts believe the predominant technology for home fabrication machines will be inkjet deposition due to the availability of printing in color (Lipson and Kurman 2011; Bourell 2011).

As customers begin to create their own designs, download digital designs from online sources, and purchase digital designs from other consumers, new business models will continue to develop. For example, consider Shapeways. Nearly anything can be designed by customers and shipped to them after manufacturing, within size and material limitations (Wohlers 2011b). A similar concept marketed by Ponoko, a New Zealand company, allows consumers to buy, sell, or trade digital designs (including many free options). They can also create entirely new designs using simplified design tools and subsequently download the finished design for home fabrication. If consumers do not yet have a home fabricator, they can get parts fabricated and shipped to them from fabrication hubs, similar to the Shapeways model (Lipson 2011).

As the technology of additive manufacturing progresses, alternatives will compete for delivering custom products to this emerging consumer market. Depending on how quickly the cost of home fabricators decreases, the future may be predominantly in downloadable designs for home fabrication (a model similar to iTunes with CD burning); downloadable designs for printing at a local manufacturing hub (similar to a Kinko's for paper copies); or central manufacturing via designs created, stored, and altered online like

Shapeways (similar to Amazon.com). One expert in personal fabrication suggested that within 5 to 10 years, many plastic parts will be fabricated in homes, but the more esoteric materials like metals, ceramics, and glass will go to a Kinko's model, at least in the near term (Lipson 2011). Regardless of the future landscape, it is likely that industry consolidation will occur in these low- to mid-level machine manufacturers as the market progresses. For instance, HP, a world leader in desktop two-dimensional printers, is now investing heavily in the technology, which may start a trend of major manufacturers getting involved in additive manufacturing (Wohlers 2011b).

Trends: Long Term

No existing industry roadmaps for additive manufacturing extend predictions to 2030. Further, the convened experts contacted for this research paper were typically hesitant to make such long-term predictions. However, their responses illustrate some of the possible advances for the technology 20 years into the future, in addition to societal ramifications.

Technology Trends

In 20 years, the technology used for additive manufacturing will be nearly unrecognizable compared with the current state of the art. In terms of the processes, most experts agreed that some new methods will be developed to correct some of the inherent problems of layer-based fabrication. This will occur through one of two potential routes. The first possibility is that the current trends will continue and accelerate, creating increasingly thinner layers of multiple materials (Stucker 2011). Achieving this while simultaneously increasing speed will likely require mass parallelization, with upwards of thousands of melt pools, nozzles, or other build vehicles that simultaneously construct material by layers (Rosen 2011). This mass parallelization would require significant technical advances, as well as improvements in the software running the machines (Stucker 2011). Likewise, under this scenario, hybridization would continue such that different processes, including subtractive ones, are all used simultaneously, with different materials in the same build space (Frank 2011; Cormier 2011). In part, this will require significant advances in understanding materials phenomena, including interfacial science and engineering. Ultimately, the goal will be understanding how materials interact at the molecular scale (Wicker 2011).

The other potential scenario is that some alternative advance will allow the elimination of layer-based processing altogether, moving toward a volume-based build. There are no currently known processes to achieve this vision, but there could be whole new ways of focusing energy in volume spaces instead of on points (Stucker 2011). One other possibility is the use of self-assembly with the aid of biological processes or nanotechnology (Frank 2011; Leu 2011).

New Design Concepts

While the processes of additive manufacturing will improve significantly, there will also be large changes in design concepts and the way product designers think about the possibilities of materials and geometry choices. This will start with education, as the increased usage of additive manufacturing in industry demands designers educated in its advantages and possibilities. Ultimately, this could lead to designers who include complicated internal geometries and multiple materials in additive manufacturing processes (Wicker 2011).

There will also be significant changes in CAD technologies, which will become easier to use to design any conceivable geometry or any combination of materials (Cormier 2011). New companies will enter the CAD software space and provide solutions for many different levels of expertise and sophistication, from the consumer market that will be slower to integrate multiple material machines up to the highest quality part design in industry. The consumer market will change the way geometries are described to computers, including input based on freehand motion, clay molds, and many other new innovations (Lipson and Kurman 2011).

Markets Where Technology Will Have an Impact

Additive manufacturing machine manufacturers will likely become established companies in 20 years, and a high degree of consolidation is expected. Process improvements and market consolidation will lead to significant price drops for consumer and industrial machines, leading to an ever-increasing use of the technology by both market segments (Stucker 2011).

Aerospace

Aerospace companies will make great use of additive techniques for producing new products and spare parts. Although prices will have dropped significantly, it is unlikely that additive technologies will be cost competitive with large-scale casting and molding. Thus, the best niche for additive techniques will continue to be lower volume and complex or custom parts, such as for satellites and military systems (Kinsella 2011). Aircraft may take advantage unique capabilities of additive manufacturing like functionally graded materials that different densities at different layers and, embedded functionality like sensors and antennae (Frazier 2011).

Twenty years from now, aircraft manufacturers want to be printing very large components, far outside of the current build size limitations (Frazier 2011). There will be heavy usage on the military side, with new designs made possible by the geometric and material advantages of additive processes. Surface-finish problems will mostly be solved, and complex cellular or porous geometries will allow significant lightweighting without sacrificing functionality. But even in 20 years, production rates may not be high enough

to penetrate the commercial aircraft market due to the large size of parts and high volume of products needed (Slattery 2011).

Medical

Significant advances will occur in the medical field in 20 years, and some will be related to additive manufacturing techniques. The current cost limitations on custom implants will likely have gone away due to advances in additive manufacturing processing and materials, such that fully customized implants will be commonplace for many types of prosthetics (Cormier 2011; Kinsella 2011; Christensen 2011a). Even for routine surgeries and implants, customized surgical models and tools will be commonplace, as imaging and additive manufacturing costs continue to lower.

Perhaps the largest change in 20 years for additive technology will be in biofabrication. Three-dimensional cancer models and drug-testing models will be in use, and they may have replaced current animal models almost altogether (Sun 2011). At least the beginnings of regenerative medicine—fabricating functional tissues and organs to repair damage—will be possible in 20 years, if not the entire concept of living organ printing (Sun 2011). Such advances will have profound implications for treating many types of illnesses.

Consumer

In 20 years home fabrication will be commonplace, and three-dimensional printers will be available to consumers and schools. It is unclear whether home fabrication of all materials will be possible, but for those that are not, the new business types in development will allow delivery to the home or local fabrication hub (Stucker 2011; Lipson and Kurman 2011).

Design capability and use of CAD software will be as common as word processing is today, with three-dimensional design and fabrication a part of everyday life for many consumers (Rosen 2011). There will likely be formal education in schools on how to create and alter three-dimensional designs, although much of the education will also probably be informal via methods similar to today's YouTube (Lipson 2011).

Barriers to Adoption

Despite considerable confidence among experts that additive technologies will have a bright future in many different markets, many barriers will have to be overcome in both the short and long term. This section discusses several of these barriers.

Funding

One of the most commonly discussed barriers was the lack of government funding. Some experts cited recent initiatives by DARPA that demonstrate an increased Federal interest in manufacturing technology (Stucker 2011; Hazelrigg 2011) but also acknowledged that large companies remain only minimally invested in the technology. Most of the investment has been made by small venture-capital firms and self-funded entrepreneurial activity (Stucker 2011). In general, both commercial and governmental research was recommended (Stucker 2011; Wicker 2011).

Cost

Despite significant advancements in recent years, additive manufacturing technology remains relatively slow, and materials are still expensive (Hazelrigg 2011; Slattery 2011; Bourell, Leu, and Rosen 2009). For example, powder metals and photopolymers are \$750–\$1000/gal compared with injection-molding material, which costs \$1/pound (Cormier 2011). As a result, although some producers see savings when using additive manufacturing for custom products and low production runs, the overall cost of processing continues to be a major impediment for larger runs (Leu 2011). Market growth, however, is expected to lessen some of these issues as new competition enters the market (Lipson and Kurman 2011). The question remains whether new competition will drive demand for additive manufacturing machines and services.

Up-front and maintenance costs of machines are another big obstacle, but a quicker time to market will help reduce the financial challenge associated with obtaining and operating equipment (Bourell, Leu, and Rosen 2009). Similarly, increasing yield rates and uptime will have a positive effect on the industry (Hazelrigg 2011). The expiration of patents will also likely reduce cost barriers and allow the technology to be implemented on a larger scale (Wicker 2011).

Even with significant growth in additive manufacturing, competition with established low-cost processes will remain. In the near term, additive manufacturing will be reserved for specialty markets and mass customization. For now, this includes low-volume parts that are not subject to significant stresses and are not safety critical. Ultimately, the specialty market will continue to grow in areas where internal geometry is complex and not easily produced via conventional processing methods (Hazelrigg 2011).

Intellectual Property, Liability, and Regulation

Several types of intellectual-property barriers could prevent additive manufacturing from being a mainstream process. In machine manufacturing, many key processing patents for additive manufacturing machines are expiring in the next 5–10 years (e.g., stereolithography, laser sintering, and FDM), which is likely to stimulate significant innovation impossible until now (Stucker 2011). But there are also serious concerns

about critical intellectual-property theft made easier by the portability of designs and ease of replication. Existing reverse-engineering technology could potentially allow design theft, something that will be of greater concern as additive manufacturing capabilities increase (Cormier 2011; Lipson and Kurman). Given the variety of designs possible, it will be difficult to define the boundaries of infringement on patent rights. Moreover, with distributed manufacturing, it may be difficult to track the number of products that are being produced from a patented design since the design and physical product are now separate entities. It may even be difficult to know whether or not a design has been copyrighted or patented. Even if digital rights management is added to design files, piracy of designs from well-known designers can be expected, similar to what happens with digital music and movies today. Such issues highlight the delicate balance between open sharing of designs and protection of intellectual property. *Patents and copyrights do not cover such work* at present (Lipson and Kurman 2011).

Similarly, liability issues will increasingly surface as component functionality grows. Most products printed to date have limited functionality, including art or prototype components, which have minimal likelihood of malfunctioning during use. In contrast, future products are likely to face increased stresses. One expert offered the fictional example of a printed steering wheel failing in a vehicle experiencing an accident. Here, it could be difficult to determine the party responsible for the accident. It could be due to faulty manufacturing, materials, or even installation. Such issues may be resolved proactively with regulations or ultimately be handled in the courts, but thus far there have not been significant efforts in this area (Lipson and Kurman 2011). One expert worried about how regulation and litigation in the United States could restrict progress in additive manufacturing technology (Wicker 2011). On the other hand, lack of regulation could also be an issue that would increase liability concerns. Finding the balance between safety and ability to bring new products to the market will be critical as additive manufacturing continues to grow.

Technological

State-of-the-art technology is still limited in speed and size. Hybrid technologies that couple additive manufacturing with subtractive processes may improve both speed and size, but it is not yet clear how best to marry existing technologies (Cormier 2011). Moreover, most machines currently have closed architecture, precluding researchers from meaningful changes to processing (Bourell, Leu, and Rosen 2009).

Another issue, especially from the manufacturer's perspective, is the low duty cycle of additive manufacturing techniques. In some cases, machines spend as much downtime as they do uptime (Slattery 2011).

For aerospace materials, lightweight, strong parts are needed, but the breadth of materials is currently limited (Bourell, Leu, and Rosen 2009; Wohlers 2011b). Surface

finish quality also remains a problem (Wohlers 2011a; Slattery 2011). One way to address this issue is to find ways to export file types from an additive manufacturing machine to a CNC machining process (Slattery 2011).

Biofabrication is an area that still faces significant barriers. There is no machine currently available that produces biological parts. One expert explained that finding the right process for biofabrication is analogous to finding the right tool in the machine shop for processing a material: the goal is to optimize process parameters for the best final product possible (Sun 2011).

Lack of Design Tools

One of the biggest barriers for additive manufacturing is the scarcity of design tools, along with the education for utilizing them (Bourell, Leu, and Rosen 2009). As a result, what is possible through additive manufacturing techniques has yet to be explored (Wohlers 2011a). Design is currently entrenched in the traditional paradigm of manufacturing, primarily three-axis machining and fastening of metal sheets. The complex designs, tailoring, properties, and embedded functionality possible through additive manufacturing demand new design frameworks (Bourell, Leu, and Rosen 2009).

Current-generation CAD struggles when handling 1000 surfaces or more, a limitation that can slow down the additive manufacturing design process. In the future, tools may be able to take distributions of mechanical properties and pick materials and shapes based on the properties, similar to the ideas driving ICME (see Chapter 3.C.2) (Bourell, Leu, and Rosen 2009). With the advent of more advanced design and CAD tools, the benefits of additive manufacturing, such as predictive analysis and modeling, can be more fully realized (Rosen 2011; Bourell 2011).

With new design and CAD tools, education will be paramount. It will be important to teach design methodologies all the way down to undergraduate levels, therefore enabling a greater diversity of concepts (Bourell 2011). At present, people do not design specifically for additive manufacturing or customer flexibility, but this is likely to change as design is more integrated with education (Rosen 2011).

Certification and Standardization

Certification is of critical importance to the progress of additive manufacturing since material properties and structural design are not yet uniform or standardized. Testing products takes time, and additive manufacturing techniques are completely different processes that require new testing methods. There is already an ongoing ASTM committee that has initiated the setting of standards (and ASTM has agreed to publish international standards with the International Standards Organization (Bourell 2011)), but

note that these standards may not be robust enough for military purposes or even for internal specifications at companies (Frazier 2011; Slattery 2011).

Efficient part certification will be assisted by closed-loop process-control systems that can help quantify the inconsistency of repeatable processes. Consistency is needed over time and across machines, operators, and facilities (Bourell, Leu, and Rosen 2009). New sensors will be needed for closed-loop control, including those for precision, surface finish, porosity, and melt pool size. Methods for inspecting the build environment during processing may also be required to make corrections as needed (Bourell 2011). Note that biological constructs will demand different sensors to monitor a range of qualities that are not necessarily identical to those in plastics- or metals-based additive manufacturing machines (Bourell, Leu, and Rosen 2009).

Some applications, including those in aerospace, are especially expensive to qualify. The rapid improvements possible from additive manufacturing are hindered by the expense of this process. One expert offered the example that a material might cost \$250,000 to qualify, but 1 year later a new material may outperform the old one and require a new qualification process (Cormier 2011). Due to the high costs of qualification, another expert suggested that significant public investment will be needed for defense applications (Slattery 2011).

Standards for communication are also needed. There is currently no standard format for electronic blueprints that allows CAD programs and printers to talk to each other. Instead, there are a number of proprietary, ad hoc formats that do not work well together. Similar to how the Internet required a common language of hypertext markup language (HTML), an agreed-upon standard is needed for communication across additive manufacturing machines (Lipson and Kurman 2011).

Another area of additive manufacturing that will require standardization is material property data generation. It must be robust and include a wide array of materials, along with their corresponding range of properties (Frazier 2011; Bourell 2011).

Scientific Understanding

Failure modes of products created via additive manufacturing are still not well understood. To move to more functional components, the failure mechanics of materials and products will need to be better characterized through advances in reliability science. In this pursuit, better modeling and simulation of microstructures will be useful. Currently, this work is very difficult for layer-based approaches (Frazier 2011).

With respect to biofabrication, numerous scientific barriers persist. In the case of in vitro models, there is a knowledge gap. Relatively few researchers are currently studying these techniques. This is true in the United States, as well as other countries, including Japan, where some promising research exists but just at the laboratory stage (Sun 2011).

Global Development Issues

Additive manufacturing may be considered a disruptive technology because it has the potential not only to affect how several products are made but also how they are designed and delivered to customers. But the benefits of the technology will likely be unequal across industries, and the technology will not affect all countries or businesses within an industry similarly. The nature of additive technologies could potentially change deeply embedded incentive structures and economic concepts that are taken for granted, such as economies of scale. This section discusses the implications for the United States and its businesses.

In terms of additive manufacturing machine production, patents for many of the established additive technologies are expiring over the next 5 to 10 years. The current global distribution of additive technology, particularly machine manufacturers, is mainly a function of these patents, and thus the industry's global distribution could change dramatically in the coming years. The United States currently has several strong companies, particularly in plastics and mid-price machines used for prototyping; however, European companies have a lead in other areas like high-end direct metal part machines. China has started to invest heavily in this technology as well, and will almost certainly compete heavily in several market segments as patents expire. Significant effort will need to be made for the United States to retain its competitive edge where it currently has one and to develop into new market segments.

Some experts expect that additive manufacturing to be a boon to U.S. manufacturing overall, because many of the processes require much less low-skilled labor than competing traditional processes. Instead of competing on labor costs, if additive manufacturing becomes a mainstream manufacturing process, firms and countries will compete on creativity and design (Rosen 2011; Lipson 2011). This could partly reverse long-standing trends like outsourcing, moving instead toward decentralized product design and manufacturing methods (Lipson and Kurman 2011). The possibility of creating parts and final goods locally also reduces shipping and inventory costs, which have increased substantially in the past decade.

Reducing the capital intensity of manufacturing through the use of additive manufacturing could have other positive impacts globally, such as helping traditionally underrepresented communities participate and compete in manufacturing markets. Developing countries could overcome their lack of capital or transportation infrastructure and design and create innovative new products specific to their needs. (Lipson 2011). Additive manufacturing thus is an equalizer between market incumbents and newcomers, allowing anyone with a new idea to produce the first prototype of a new product very inexpensively. This change, sometimes known as the “scale up from one” property of additive technology, allows designers to try out a design and sell it in small quantities with little capital risk, scaling up to faster and larger scale manufacturing only once a

design has been perfected and its market assured. Thus, parts of the global manufacturing industry could change drastically over a short time period. Much as the Internet democratized media and music markets, the dominance of incumbent manufacturers, particularly those of products with merely adequate or subpar designs, could be severely threatened by new companies taking advantage of these processes (Lipson and Kurman 2011).

Appendix I.

Biomanufacturing and Synthetic Biology

Introduction

Molecular Biology and Synthesis of Biological Products

Humans have been manufacturing products using biological systems for millennia. The production of alcoholic beverages through fermentation processes dates back to before 6000 BC. More recently, sugarcane and other crops have been domesticated and cultivated for the production of sugar. However, these processes use biological systems that exist in nature, and scientists did not attempt to engineer such systems until recently.

The discovery of the genetic code and the ability to manipulate it in the latter half of the twentieth century allowed scientists to understand biological systems at the molecular level. Deoxyribonucleic acid (DNA) sequences called “genes” encode all the functions within a cell. Some DNA sequences code for protein and ribonucleic acid (RNA) molecules that are capable of performing molecular functions such as catalysis (enzymes) or control the production of other proteins (transcription factors). The production of proteins (gene products) from the encoding DNA is the “gene expression program” of the cell. The advent of recombinant DNA technology gave researchers the ability to add, remove, and alter sequences of DNA to produce new products and better understand the metabolic functioning of living cells.

Engineering bacteria and other cells on a small scale has led to great strides in understanding control of gene expression. DNA sequences called “genetic elements” are involved in complex genetic circuits that control many different functions of the cell such as metabolism, growth, death, and response to external stimuli through up-regulation or down-regulation of gene expression. The control that the cell exercises over the production of gene products makes it a coveted system for engineers to exploit.

Current manufacturing of products using biological systems is generally limited to chemical purification of naturally produced products or genetic manipulation of microbial or mammalian cells to produce the desired products. Each method has its drawbacks. For the former, an adequate supply of the biological system that produces the desired product must be cultivated (for example, sugarcane for producing sugar), creating a logistical burden. The latter involves simple genetic manipulation of a system, with limited ability to optimize the design of the producing cell. In most cases, genetic engineers incorporate the gene for a product into a cell under the control of genetic elements that up-regulate

expression. Lacking a rigorous understanding of the complete system, these engineers are unable to predict if the method will be successful. The field of synthetic biology attempts to address these drawbacks.

Synthetic Biology

Breakthroughs in several areas of biology have changed the way scientists view biological systems. Traditionally, biologists took a reductionist approach to understanding the cell and engineering it for applications. They typically manipulated a single gene and the genetic elements that regulate its expression to try to understand its function within the cell. With the advent of rapid DNA sequencing, researchers are now able to analyze entire genomes and compare genetic elements across different organisms (genomics). Furthermore, mapping the entire protein content of a cell (proteomics) provides an understanding of the number of proteins that could be engineered for manufacturing purposes. Coupling these advances in genomics and proteomics with computational methods (bioinformatics) enables biologists to study the entire cell as a system. Systems biology tries to understand not only a particular gene and its regulatory elements, but also the vast genetic network in which the gene resides (Kitano 2002). Systems biology stresses computational methods to model and understand these networks. Engineers often liken the cell's genetic network to an electric circuit. Here, information flows like electricity via the various genetic elements and proteins that constitute the component parts of the network. In this view, a certain level of modularity is brought to biology, such that parts can be exchanged into and out of the circuits to bring new functionality (Endy 2005).

This multidisciplinary emerging technology area introduces engineering approaches of modularization, modeling, and a rational and iterative design cycle¹ to molecular biology to exercise precise control over cell functions and products (Koide, Pang, and Baliga 2009).² Advances in genomics, proteomics, systems biology, and genetic engineering have allowed engineers to catalog and standardize genetic elements as parts. With a toolbox full of standardized parts, it may be possible in the future to design a new synthetic biological system using a rational engineering cycle. If the goals of synthetic biology are realized, a future engineer would be able to define the specification of the

¹ See *Stanford Encyclopedia of Philosophy*, "Rationalism vs. Empiricism," First published Thu Aug 19, 2004; substantive revision Wed Aug 6, 2008; <http://plato.stanford.edu/entries/rationalism-empiricism/>.

² Current genetic engineering techniques involve manipulating DNA sequences mostly by trial and error to achieve desired goals, even without complete understanding of, and predictive capability within, the system. A rational approach implies that the system is well understood and any engineering can be performed with reasoning and hypothesis behind each experiment. If the experiment fails, intelligent troubleshooting will be able to determine causes of unexpected results. Generally, this rational approach is lacking in most genetic engineering work due to a lack of adequate understanding of the biological system.

system desired and design it with the available genetic parts. As part of the design, computer modeling would be implemented to simulate the expected behavior of the circuit. These results from the design stage would then be implemented by designing synthetic DNA and inserting it into a standardized cell for producing the desired product.

The field of synthetic biology is still in its technical infancy, with many technical hurdles to overcome before reaching these goals. The current state of the art involves the design of simple genetic-element circuits to perform simple functions. Basic research is being done to standardize cells for optimizing production of desired products. Attempts are being made to remove extraneous functions and produce a “minimal cell” containing the minimal genome necessary to allow the cell to reproduce and perform its synthetic biology function (Jewett and Forster 2011). The cell would then become a “chassis” to which synthetic DNA molecules can be added to meet the specifications of the design. Synthetic biology also seeks to expand the capabilities of molecular biology by expanding the genetic code and the repertoire of amino acids and other biomolecules (Wang, Parrish, and Wang 2009). This has the potential to permit new chemistries to be produced by biological systems (Glieder and Pscheidt 2008). It should be emphasized that all of these efforts are still in the research laboratory stage, although there are examples of manufacturing successes that employ synthetic biology principles that hint of the potential of the discipline to impact biomanufacturing.

To achieve this biology engineering cycle, synthetic biology would need to incorporate a number of disciplines from traditional molecular and computational biology. The following disciplines contribute to the design, modeling, implementation, and test and evaluation of a synthetic biology system:

- *Genomics (design)*—Rapid DNA sequencing of whole genomes of organisms and construction of vast DNA sequence databases to compare and contrast genetic elements.
- *Genome Mining (design and modeling)*—Mining involves searching databases of genomic data for a gene or genetic element with a desired function.
- *Systems Biology (design and modeling)*—Systems biology looks at biological systems through a holistic, rather than reductionist, approach. It actually builds on the foundation of reductionist knowledge and attempts to incorporate mathematical modeling of complex biological systems. An example would be a model (or prediction) of gene expression within the context of the entire cell, rather than studying the gene expression of a single gene alone.
- *Genetic Engineering (implementation)*—Genetic engineering involves manipulation of DNA sequences and creation of engineered organisms through use of recombinant DNA technology.

- *Metabolic Engineering (implementation)*—Metabolic engineering uses recombinant DNA methods to improve production of chemical and protein products by an organism (Keasling 2010).
- *Engineered Biosynthetic Pathways (implementation)*—This involves assembly of novel synthetic pathways by combining genes from multiple sources or fine tuning existing pathways in *E. coli* or other expression systems (Yadav and Stephanopoulos 2010).
- *Cell Chassis (implementation and testing/validation)*—This discipline uses cells with minimal genomes to produce a desired bioproduct. It typically involves rewiring through synthetic biology to optimize production and remove undesirable functions. Current research efforts are to develop a cell with a “minimal”³ genome complement to simplify metabolism. Research indicates that this simplification of the genome has the benefit of improving the ability of the resulting cell chassis to accept synthetic DNA (transformation), maintain synthetic DNA (stability of plasmids), and increase protein yield (Pósfai et al. 2006).

Rationale for Selection Based on Criteria

We classify synthetic biology as an emerging technology in the manufacturing sector for the following reasons:

- It has potential to affect multiple industries.
- It has potential national security applications.
- U.S. R&D investment in synthetic biology is growing.

These reasons are explored in detail in the next sections.

Synthetic Biology and Advanced Manufacturing Trends

Synthetic biology is still immature, so its influence in the area of manufacturing is still uncertain. However, a group led by Jay Keasling at Lawrence Berkeley National Laboratory, University of California, Berkeley, has successfully applied synthetic biology techniques to the synthesis of the antimalarial drug artemisinin within a cell chassis derived from yeast. This achievement demonstrates some of the potential of synthetic biology in the pharmaceutical manufacturing sector and serves as an example of how synthetic biology conforms to advanced manufacturing trends.

Artemisinin is a compound derived from the sweet wormwood plant. It has been used in traditional Chinese medicine for centuries. In the 1970s Chinese researchers

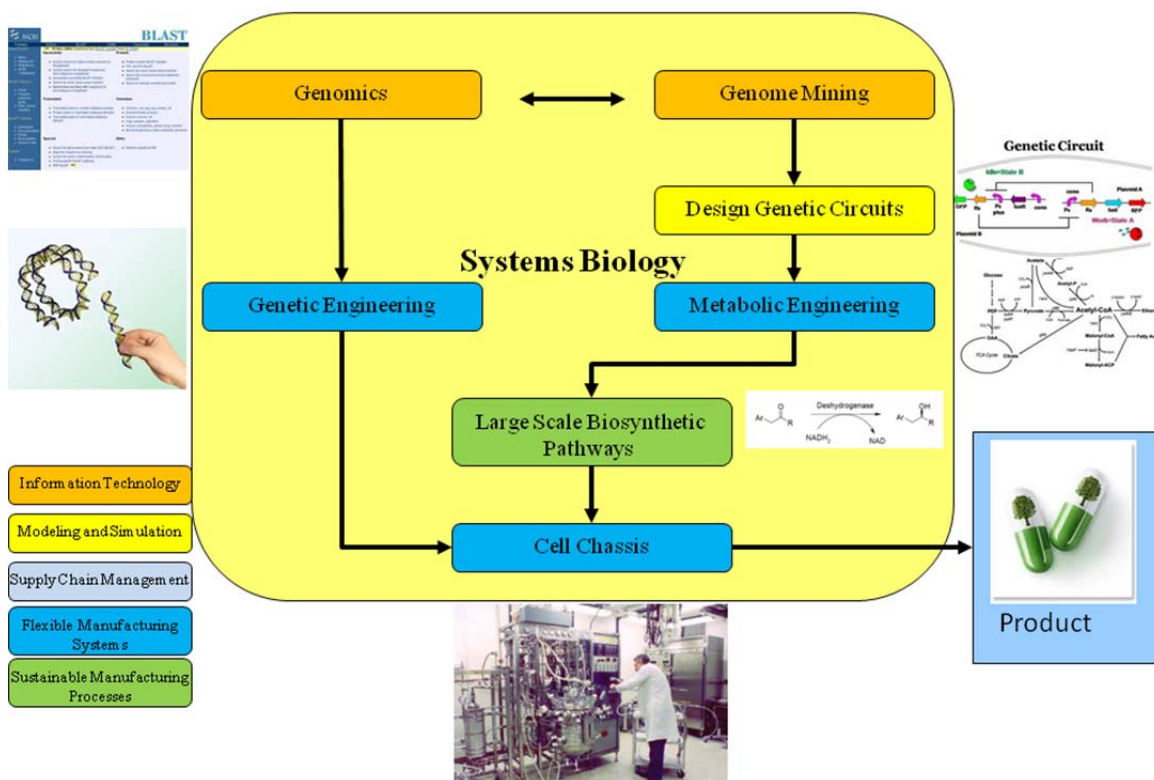
³ It is unclear in the research community what constitutes a minimal genome.

discovered that artemisinin was effective in killing the malaria parasite *Plasmodium falciparum*, and further work resulted in more potent derivatives of artemisinin (Enserink 2005). Because the malaria parasite is becoming resistant to traditional treatments, artemisinin is an excellent candidate to help fight drug-resistant strains of *Plasmodium falciparum*. Unfortunately, artemisinin and its derivatives are difficult to produce. First, the sweet wormwood plant is primarily cultivated in China and Vietnam, and farmers are reluctant to produce the plant, producing more valuable crops instead. Second, extraction of the natural compound and chemical synthesis of derivatives are costly, produce low yields, and are not environmentally friendly.

Keasling's group used synthetic biology principles to insert genes of the sweet wormwood plant into yeast cells to form an active biosynthetic pathway producing artemisinic acid, a precursor to artemisinin (Ro 2006). This synthetic biology process demonstrates several advanced manufacturing principles:

- The project used modeling and bioinformatics (information technology) techniques to design the yeast system and determine the necessary genes for optimal production of artemisinic acid in yeast.
- The supply chain for production has been simplified by eliminating the need for the sweet wormwood plant from China and Vietnam.
- The manufacturing process was made more sustainable by reducing chemical transformations and increasing biotransformations, which are more environmentally friendly (Tao and Xu 2009).

The artemisinin example demonstrates that synthetic biology may be capable of affecting pharmaceutical manufacturing and has potential to simplify difficult manufacturing problems and make them more tractable and sustainable. Figure I-1 illustrates the idealized application of synthetic biology to pharmaceutical manufacturing, which was only partly achieved in the artemisinin example.



Notes: Figure demonstrates the interplay between the molecular biology disciplines introduced in the text above in a methodology to produce pharmaceutical products using synthetic biology methods. Molecular biology methods are colored according to their applicability to advanced manufacturing principles described above in the text (color key is located at the lower left in the figure). Systems biology (in yellow, impacting all the disciplines), genomics, genome mining, and genetic engineering are used to design the desired genetic circuit. This genetic circuit can then be optimized through metabolic engineering to design a complete biosynthetic pathway. The pathway design would include synthetic regulatory circuits and other control mechanisms designed to achieve optimal levels of product synthesis. The genes specifying the pathway and the regulatory elements would then be inserted into a standardized cell chassis developed using genomics and genetic engineering techniques. The engineered chassis is then used to manufacture the desired product.

Figure I-1. Application of synthetic biology to pharmaceutical manufacturing.

Synthetic Biology as a Platform for Multiple Industries

Synthetic biology could be an enabling technology for industries other than pharmaceuticals (Royal Academy of Engineering 2009):

- *Chemicals*—Biocatalysis enhanced through synthetic biology can be used not only for pharmaceutical manufacturing but also for production of fine chemicals (Yadav and Stephanopoulos 2010).
- *Biofuels*—Production of biodiesel and ethanol from cellulosic biomass is a priority for the Department of Energy, but current processing technologies are inefficient and costly.

- Biodiesel can be produced by inexpensive conversion of plant oils and waxes to fatty acid methyl esters, but optimal biodiesel production would have plants carry out photosynthesis and produce and store oils. This paradigm would require large-scale engineering of plant cells by metabolic engineering, systems biology, and potentially synthetic biology.
- Ethanol production from cellulose-based biomass faces similar technical challenges. Plants and plant mass have evolved to resist breakdown by microbes and pests; however, it is necessary to degrade the mass into polysaccharide components to produce ethanol. One possible solution is to design crops that can easily degrade, resulting in a heterogeneous mix of sugars, which can be transformed with enzymes to ethanol. A goal would be the development of a set of “multitalented” robust microorganisms that can transform the sugars to ethanol more efficiently. The ultimate goal would be the development of self-replicating synthetic microbes to support all stages of ethanol fuel production (DOE 2006).
- *Sensors*—Synthetic biology could lead to the design of new molecules and systems for sensing the environment for hazardous chemicals (Khalil and Collins 2010).
- *Agriculture*—Seeds could be engineered through synthetic biology to have multiple genetic traits for hardiness. Crops could also be engineered to improve yields and nutritional value. Finally, biomass from agriculture could be optimized for biofuel production (Steen et al. 2010).
- *Materials*—A canonical example of a valuable biomaterial is spider silk (Foo and Kaplan 2002). These silks are composed of fibrous proteins that, when spun by a spider, have unique strength and other desirable mechanical properties. The potential to genetically alter proteins such as spider silk to improve biocompatibility, stability, and flexibility make them attractive to engineers as a source of advanced biomaterials. Producing silk proteins synthetically in recombinant systems has been difficult for a number of reasons. In particular, recombinant systems do not tolerate sequences present in spider DNA. Also, synthetic silk proteins produced in bacterial cells tend to aggregate and are useless to spin into polymers. Widmaier et al. (2009) therefore redesigned the natural spider silk DNA sequence to be more amenable to recombinant systems and engineered a *Salmonella* expression/excretion system for production. A genetic control circuit was also designed into *Salmonella* such that the synthetic DNA is only transcribed when the cell is actively secreting the protein.
- *Computing*—Logic gates have already been produced with synthetic biology techniques, and biological computing may be possible in the future (Gardner,

Cantor, and Collins 2000). The key is for synthetic biology to be able to construct useful next-generation synthetic gene networks rather than just simple logic gates, that could have potential real-world applications (Lu, Khalil, and Collins 2009).

Synthetic Biology and National Security

The Department of Health and Human Services (DHHS) released a National Health Security Strategy in December 2009 to “galvanize efforts to minimize the health consequences associated with significant health incidents” (DHHS 2009). It outlines a strategy to increase public health and the nation’s capacity to respond quickly and efficiently to pandemic and bioterrorism threats. The DHHS Secretary then called for a review of the U.S. medical countermeasures (MCM) enterprise and its ability to quickly develop, deploy, and use MCM (DHHS 2010).

One of the findings of the review is the need to improve domestic manufacturing capacity by embracing “nimble, multiuse technology platforms and products, when appropriate, to increase the likelihood of developing and procuring products in a cost-efficient and timely way that constitutes responsible stewardship of resources”. As the artemisinin example demonstrates, synthetic biology has the potential to provide a flexible platform for MCM production. However, significant advances in making synthetic biology modular, repeatable, and universal are required before it will become a platform for the MCM enterprise.

The Department of Defense, a partner in the U.S. MCM enterprise, recognizes the importance of synthetic biology to national security. The Assistant Secretary of Defense for Research and Engineering identified synthetic biology as a priority technology (Weinberger 2010). The Department is interested in how organisms sense and respond to chemical, electrical, magnetic, and mechanical stimuli at the genetic level and in using that information to develop living sentinels that can sense the environment for explosives, hazardous chemicals, and other threats. The Office of Naval Research has a project to biosynthesize targeted antibiotics, and the Defense Advanced Research Projects Agency (DARPA) has recently requested proposals for a Living Foundries Program in the Microsystems Technology Office to “develop new tools, technologies and methodologies to transform biology into an engineering practice...” (DARPA 2011). The Assistant Secretary of Defense for Research and Engineering says that the Department of Defense is also interested in developing new tools to detect use of synthetic biology by an adversary. Synthetic biology has been under scrutiny from the time it was postulated that synthetic biology systems could be engineered to be pathogens and hence bioweapons.⁴

⁴ National Science Advisory Board for Biosecurity, “Addressing Biosecurity Concerns Related to Synthetic Biology” <http://oba.od.nih.gov/biosecurity/pdf/NSABB%20SynBio%20DRAFT%20Report-FINAL%20%282%29%206-7-10.pdf> , accessed December 8, 2011.

Understanding the limits of such a capability and developing appropriate countermeasures are warranted.

A further spin-off of the synthetic biology discipline is the “DIYbio” (do-it-yourself amateur biology) movement. Many amateur scientists are performing synthetic biology experiments in their homes or community laboratories both in the United States and internationally (Penders 2011). There is some concern about the safety and security of this practice (Farrell 2011). Because many of these individuals are affiliated with universities and have access to tools, reagents, and expertise, these concerns may be valid. Concerns range from membership of these amateur groups and the ability of terrorist groups to exploit the capability of amateurs in the development of a weapon of mass destruction (WMD). It is well known, that Al-Qaeda is interested in developing a chemical or biological WMD.⁵

Energy supplies are another national security concern. The United States currently relies heavily on fossil fuels for energy requirements and consumes 25% of global oil produced (DOE 2006). U.S. domestic oil reserves only account for 3% of the world’s known reserves; 60% of the world’s reserves reside in sensitive and volatile regions of the globe. Biomass feedstocks, on the other hand, are domestic, secure, and abundant. These qualities make biofuels an attractive alternative to foreign oil. As with other examples in this section, with significant research investment and meeting a number of technical challenges, synthetic biology techniques may advance the production of biofuels more efficiently.

U.S. R&D Investment in Synthetic Biology

The Woodrow Wilson International Center for Scholars performed a study of synthetic biology investment by U.S. Federal agencies and by countries within the European Union (Woodrow Wilson International Center for Scholars, 2010). The center found the United States averages roughly \$140 million dollars per year in synthetic biology research; the European Union averages about one-third to one-quarter that level. But the report notes that these funding levels are an estimate and may not be entirely accurate. It is clear that the definition of synthetic biology research in this report is broad, including genomics, DNA sequencing, and biosensor research. Further research is needed to determine a more accurate estimate of funding for “true” synthetic biology R&D.

According to the Wilson Center report, the U.S. Department of Energy provides the most funding in this area for investigating bioenergy. The U.S. DHHS and the National Science Foundation have provided about \$40 million each in synthetic biology grants

⁵ *Inspire Magazine*, <http://publicintellgence.net/complete-inspire-al-qaeda-in-the-arabian-peninsula-magazine-issue-2-fall-2010/>, accessed December 8, 2011.

since 2005. Data for the Departments of Homeland Security and Agriculture appear to be incomplete.

The United Kingdom has at least one research center at the Imperial College of London. The Centre for Synthetic Biology and Innovation is funded by the United Kingdom's Engineering and Physical Sciences Research Council.⁶ The center is composed of about 10 researchers who study technical, social, policy, and biosecurity issues associated with synthetic biology. Synthetic biology centers exist at the Universities of Oxford and Edinburgh, and the European Union has three synthetic biology centers at the University of Groningen in the Netherlands, the Swiss Federal Institute of Technology, and the University of Freiberg (Panke 2009).

China has recently developed an interest in synthetic biology with research goals similar to those of the United States, such as genetic circuits, minimal synthetic cells, synthetic proteins, and synthetic nucleic acids (Pei, Schmidt, and Wei 2011). Applications for this technology are also similar—biofuels, bioremediation, minimal cells, novel biochemical synthesis, and chassis development. For example, Qindao Institute of Bioenergy and Bioprocess Technology is developing genetic circuits to produce fatty-acid biofuel in cyanobacteria, and the Key Laboratory of Synthetic Biology is developing genetic circuits to produce butanol in *Clostridium acetobutylicum*.

Like western countries, China is having trouble defining the field and assessing its impact. Much biotechnology funding in China is through government programs such as the 863 Program (National High-tech R&D Program), the 973 Program (National Basic Research Program of China), and the National Science Foundation of China. Currently, synthetic-biology efforts are spread among these three programs. For example, the 973 Program is funding 40 million Chinese yuan per year (about \$6.4 million in U.S. dollars per year) for a program to develop an artificial synthetic cell factory. A dedicated research funding strategy has been proposed in China for synthetic biology, but it has been delayed due to a lack of a consensus definition for the discipline.

One outgrowth of the discipline of synthetic biology is the International Genetically Engineered Machine (iGEM) competition. Each year academic student teams from all over the world compete for prizes to develop the best synthetic-biology project with the goal to develop new biological parts.⁷ The iGEM teams come from the United States, Canada, Mexico, South America, Europe, and Asia.⁸ China, India, and Japan are highly represented at these competitions. Each team is associated with a university and academic faculty, which implies that these represented countries have efforts, or at least interest, in

⁶ Centre for Synthetic Biology and Innovation Main Page, <http://www3.imperial.ac.uk/syntheticbiology>, accessed December 8, 2011.

⁷ iGEM Main page, http://2011.igem.org/Main_Page, accessed December 8, 2011.

⁸ iGEM 2011 teams, http://igem.org/Team_List?year=2011, accessed December 8, 2011.

synthetic biology. Many former iGEM teams develop amateur biology groups who remain affiliated with their university. Some of these amateur groups apply for government research grants and obtain funding.⁹

Interviews with Experts in Synthetic Biology

Armed with the foregoing information from published reports and journal articles on synthetic biology and its application in manufacturing, we interviewed three academic research experts and asked them for their assessment of the field and future capabilities of synthetic biology techniques in manufacturing.

One of the major takeaways from these interviews is that the term “synthetic biology” was defined differently by those we interviewed. It is usually described in terms of its future potential rather than in terms of what the field actually encompasses. Unfortunately, this has led to high expectations for the technology and the labeling of synthetic biology as a “buzzword” with little meaning. The goals for the interviews were to try to understand how synthetic biology differs from other bioengineering techniques and to develop a realistic understanding of the state of the art and potential for the technology to be applied to the biomanufacturing of products.

What Is Synthetic Biology?

Adam Arkin, Dean A. Richard Newton Memorial Professor of Bioengineering in the Department of Bioengineering of University of California, Berkeley, and Director of the Physical Biosciences Division of Lawrence Berkeley National Laboratory, sees synthetic biology as a field that tries to build a large toolbox of biological techniques and technologies to truly understand biological systems. These tools would make biological systems more amenable to engineer in order to manufacture products.. Until recently, bioengineering “wasn’t really engineering” in his view. It was more like DNA editing, a simple first step toward the ability to manipulate biological organisms to manufacture a desired product. These edited organisms make the product at the expense of its own needs for growth and maintenance, which is inefficient. Synthetic biology would expand genetic-engineering techniques by developing a toolbox that might represent a set of understood, predictable techniques and systems that can be manipulated to produce a desired product efficiently. Streamlining microbes by removing extraneous pathways and optimizing those cells for synthetic manufacturing would be important in synthetic biology.

⁹ DIYBIOMCR, “DIY Biology: Manchester gains funding for innovative new ‘citizen science’ partnership,” accessed September 12, 2011, <http://diybio.madlab.org.uk/news/files/afeb13c42d38a4e543802ac55081147f-0.php>.

An (anonymous) professor at a major academic institution sees synthetic biology a little differently. In his view, standardizing biological parts and using them interchangeably on a biological platform as “plug-and-play” modules is a bit naive. He sees synthetic biology less as a scientific discipline and more as a set of goals to manipulate information flow in living systems for a human purpose. Synthetic biology goals such as producing synthetic organisms and synthesis of useful products can be achieved by developing tools and methods to manipulate information flow in an organism. Unlike some researchers in the synthetic biology community, he favors using evolutionary processes to develop robust synthetic biology tools and methods rather than the top-down engineering approach of synthesizing biological parts. He points out that engineering approaches poorly predict complex systems like biological organisms and maintains that researchers should use a methodology at which organisms are inherently proficient, such as evolutionary processes.

Peter Carr, a synthetic biologist from Massachusetts Institute of Technology’s Lincoln Laboratory, agrees with the perspective that synthetic biology will rely mainly on “traditional” molecular biology techniques such as evolutionary process and genetic engineering in the short term. However, he believes that synthetic biology will be a discipline that brings an engineering perspective to biology. He cites the work of Drew Endy and Tom Knight, who see synthetic biology as a means of bringing predictability to biological systems. As an example, Carr cites the current practice of producing recombinant proteins in systems such as *E. coli*. Today, there are standard protocols and commercial products for producing proteins in *E. coli*, yet there really is no way to predict beforehand if the protein a researcher wishes to produce will work in these systems. It is a trial-and-error process, and a researcher who cannot produce a protein in this system can only troubleshoot using simple hypotheses before giving up and trying another system. If the *E. coli* system were completely understood and simplified to only produce recombinant proteins, producing proteins with high yields and troubleshooting production failures through an engineering-cycle approach would be much easier.

Impact of Synthetic Biology on Future Manufacturing

The current state of the art in synthetic biology extends work in genetic and metabolic engineering to produce chemicals in biological systems such as the artemisinin example mentioned previously. Another thrust in synthetic biology is the exploitation of sensing molecules (such as antibodies, proteins, and nucleic acids) by having them under control of simple logic gates. These sensing moieties can then be used in human health applications to identify cancerous or healthy cells in the body.

The artemisinin project has been criticized as being merely a metabolic engineering achievement. However, Arkin argues that synthetic biology elements exist in the work since several enzymatic pathways had to be applied and engineered rather than simply

tweaking current pathways. Development of these enzyme pathway “tools for the toolbox” classified this work as synthetic biology. Therefore, this work may be seen as a step toward synthetic biology goals. The example of logic gates controlling sensing molecules can also be seen as simple genetic engineering. However, the same argument can be applied in this example. Logic gates can represent a small step for the emerging discipline of synthetic biology that may lead to the larger goal of manipulating systems on a large scale.

It is likely that in the near term (5–10 years) new tools will be developed capable of manipulating biological systems. For example, new enzyme pathways will be discovered and others will be combined to improve the chemistry that can be performed in biological systems. The design of new proteins with new functionality will also be explored along with ways to globally manipulate genomes (Karanicolas et al. 2011; Isaacs et al. 2011). Also, generalized platforms for manipulating proteins have been developed and are important for development in the future (Esvelt, Carlson, and Liu 2011). Concurrently, these tools will be used in applications to manufacture chemicals such as pharmaceuticals and biofuels. All three scientists interviewed for this study generally agree with this assessment.

Further in the future (10–25 years), synthetic biology may develop generalized biological platforms for producing chemicals. Those interviewed see it as less likely that a generalized chassis would be used for every manufacturing application and found it difficult to predict when these platforms would be developed. It is more likely that several platforms would need to be developed and customized for individual applications. Manufacturing of materials in biological systems was seen to be something that would develop in the far future. Structural materials would be difficult to manufacture in biological systems since materials, in addition to a chemical make-up, have a three-dimensional structure that may be difficult to reproduce through enzymatic or chemical means. A more refined control of spatial and temporal reactions will be required to realize these types of materials.

Conclusions

Synthetic biology is a young field that is just beginning to make some proof-of-principle impacts; it is too soon to assess what its full impact will eventually be. For example, despite the enthusiasm artemisinin achievement brings to the synthetic biology community, the commercialization of the technique by Amyris, Inc., is still ongoing. Reports that 150 man-years of labor have already been devoted to the project (Kwok 2010) indicate how difficult it is to engineer cells and control their production of specific products. Further, rewiring the cell may not be as simple as proponents of synthetic biology indicate. Criticism has been directed at proponents underestimating the difficulty of rewiring the cell with standardized parts. It is generally downplayed that only a small

number of parts have been standardized and the parts do not always work well together. Another concern is that synthetic-biology proponents underestimate the complex biochemical networks that a cell contains.

If synthetic biology is to fulfill its promise, research advancements are needed in genomics, systems biology, metabolic engineering, and evolutionary engineering. More work is also needed in the area of systems biology to understand and model cellular information networks before progress can be made in manipulating that information flow for synthetic purposes. Likewise, the development of synthetic organisms designed to perform synthetic functions requires similar advancements in genomics, synthetic biology, metabolic engineering, and evolutionary engineering. These already established fields are more mature than synthetic biology and could easily make great contributions to manufacturing across similar sectors of industry in the near term. Once synthetic-biology tools mature, they can begin to make impacts in manufacturing, but it will likely require crosscutting research in many areas of biology, information technology, and engineering.

In the near term, work will continue on developing the minimal genome/cell chassis and standardizing genetic parts. Work will also continue to expand (1) the limits of chemistry and biology that engineered biological systems can perform and (2) the number and diversity of chemicals and materials that synthetic biology systems can produce. This work includes altering and expanding the genetic code and the repertoire of amino acids and enzymes to create new parts with novel chemistries and biological functions and to create microorganisms and cells resistant to infectious agents (Isaacs et al. 2011).

In the short term, substantial basic research and engineering needs to be conducted and policy issues need to be addressed before synthetic biology can become a mature manufacturing platform. To truly unlock the potential of this discipline, synthetic biology needs to demonstrate that it is possible to design higher order genetic networks rather than the simple circuits it is currently capable of producing. Development of the minimal cell chassis, a “tool box” of manipulatable synthetic organisms, and making bioengineering with modular “parts” more standardized, repeatable, and universal are required game-changers for the field. These tools would enable synthetic biology to be a platform for biomanufacturing. As with any immature technology, technical barriers may prove difficult. In particular, the basic research and fundamental knowledge concerning biological systems, especially at the molecular level, are also relatively immature. Nontechnical barriers such as regulation of genetically engineered organisms will also need to be addressed as the technology matures, as well as intellectual property, ethical, biosafety, biosecurity, and social issues (Royal Academy of Engineering 2009).

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Abbreviations

AIM	Accelerated Insertion of Materials
AMHS	Automated Materials Handling Systems
AMD	Advanced Micro Devices
AMT	Advanced Manufacturing Technology
AR	Augmented Reality
ASEE	American Society for Engineering Education
BLS	Bureau of Labor Statistics
BRIC	Brazil, Russia, India, and China
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAS	Chinese Academy of Sciences
CIA	Central Intelligence Agency
CIM	Computer-Integrated Manufacturing
CMOS	Complementary Metal Oxide Semiconductor
CNC	Computer Numerically Control
DARPA	Defense Advanced Research Projects Agency
DHHS	Department of Health and Human Services
DOD	Department of Defense
DOE	Department of Energy
EADS	European Aeronautic Defense and Space Company
EDI	Electronic Data Interchange
EMEA	Europe, the Middle East, and Africa
EU	European Union
FDM	Fused Deposition Modeling
FeRAM	Ferroelectric Random Access Memory
FET	Future and Emerging Technologies
FMS	Flexible Manufacturing Systems
GCI	Global Competitiveness Index
GDP	Gross Domestic Product
GERD	Gross Domestic Expenditure on Research and Development
GPGPU	General-Purpose Graphical Processor Unit
IC	Integrated Circuit
ICME	Integrated Computational Materials Engineering
ICT	Information and Communication Technology
IDM	Integrated Device Manufacturer
iGEM	International Genetically Engineered Machine
IMS	Intelligent Manufacturing System
IP	Intellectual Property
IPO	Intellectual Property Office (UK)

IT	Information Technology
ITA	International Trade Administration
ITAR	International Traffic in Arms Regulations
ITRS	International Technology Roadmap for Semiconductors
KET	Key Enabling Technology
KTP	Knowledge Transfer Partnership
LDA	Local-Density Approximation
LED	Light-Emitting Diode
MCI	Manufacturing Competitiveness Index
MCM	Medical Countermeasures
MCT	Ministry of Science and Technology (Brazil)
MEMS	Microelectromechanical System
METI	Ministry of Economy, Trade and Industry (Japan)
MEXT	Ministry of Education, Culture, Sports, Science and Technology (Japan)
MOST	Ministry of Science and Technology
MRAM	Magnetoresistive Random Access Memory
NASA	National Aeronautics and Space Administration
NEMS	Nanoelectromechanical System
NGL	Next-Generation Lithography
NMAB	National Materials Advisory Board
NRC	National Research Council
NSB	National Science Board
OECD	Organisation for Economic Co-operation and Development
ONR	Office of Naval Research
PCAST	President's Council of Advisors on Science and Technology
PC	Personal Computer
PPP	Public-Private Partnership
R&D	Research and Development
RAM	Random Access Memory
REE	Rare Earth Element
RF	Radio Frequency
RFID	Radio Frequency Identification
SBE&S	Simulation-Based Engineering and Science
SEMATECH	Semiconductor Manufacturing Technology
SFTC	Scientific Forming Technologies Corporation
SIA	Semiconductor Industry Association
SIP	System in Package
SME	Small and Medium Enterprise
SMLC	Smart Manufacturing Leadership Coalition
SoC	System on Chip
SRC	Semiconductor Research Corporation
STEM	Science, Technology, Engineering, and Mathematics
TSMC	Taiwan Semiconductor Manufacturing Company

TSV	Through-Silicon Vias
UK	United Kingdom
UNCTAD	United Nations Conference on Trade and Development
VAC	Virtual Aluminum Castings
VC	Venture Capital
VLSI	Very-Large-Scale Integration
WEF	World Economic Forum
WIPS	World Investment Prospects Survey
WMD	Weapon of Mass Destruction
WTEC	World Technology Evaluation Center

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