White Papers on Advanced Manufacturing Questions

Prepared for the Advanced Manufacturing Workshop of the
President's Council of Advisors on Science and Technology's
Study on Creating New Industries through Science, Technology, and Innovation

DRAFT

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Disclaimer: This document is a draft analysis of the scientific, technical, and policy issues regarding advanced manufacturing. It was prepared by the Science and Technology Institute (STPI) for use by the President's Council of Advisors on Science and Technology (PCAST). STPI is a federally funded research and development center (FFRDC) for the Office of Science and Technology Policy (OSTP). The analysis was conducted by STPI and does not represent the views of PCAST or OSTP.

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Foreword

Overview

This set of white papers was prepared at the request of the Office of Science and Technology Policy (OSTP) as input for the Advanced Manufacturing Workshop of the President's Council of Advisors on Science and Technology (PCAST) Study on Creating New Industries through Science, Technology, and Innovation. The papers are meant to present issues, stimulate thought, and frame discussion. The questions they address were provided by the PCAST study co-chairs as the agenda for the workshop. In preparing these papers, STPI staff reviewed the current literature and held discussions with the following experts in industry and academia:

- Yung C. Shin, Donald A. and Nancy G. Roach Professor of Advanced Manufacturing, Purdue University
- Sanjay Sarma, Associate Professor of Mechanical Engineering, Former Chairman of Research & Co-Founder of the Auto-ID Center at MIT, Massachusetts Institute of Technology
- Albert Link, Ph.D. Professor of Economics. Science and Technology Policy, UNC Greensboro
- David Audretsch, Distinguished Professor and the Ameritech Chair of Economic Development and Director of the Institute for Development Strategies at Indiana University, Indiana University
- Paul Fowler, Research Director & NACFAM Weekly Editor, National Council for Advanced Manufacturing
- Chuck Williams, Senior Vice President of Supply Chain and Manufacturing in North America, and Lukas Ruecker, Senior Vice President of Strategy in North America, Luxottica Group
- Lord Bhattacharya, Professor of Manufacturing Systems, University of Warwick
- Richard Lester, Founding Director of the Industrial Performance Center and Professor and Head of the Department of Nuclear Science and Engineering at the Massachusetts Institute of Technology, Massachusetts Institute of Technology
- Warren Seering, Professor of Mechanical Engineering and Professor of Engineering Systems, Massachusetts Institute of Technology
- Irene Petrick, Professor of Practice , Pennsylvania State University
- Martin Culpepper, Associate Professor of Mechanical Engineering , Massachusetts Institute of Technology
- Lewis Branscomb, Professor emeritus of Public Policy and Corporate Management, Harvard University
- Bruce Brown, Chief Technology Officer; R. Keith Harrison, Global Product Supply Officer; and Paul Fox, Corporate External Relations, Proctor & Gamble

To provide an initial focusing of our efforts to address these questions, STPI first looked into the definition of "advanced manufacturing," as is discussed below.

What Is Advanced Manufacturing?

Several perspectives on what constitutes advanced manufacturing have been offered by leading experts, businesses, and government organizations. The following paragraphs lay out these various perspectives as understood from discussions with leading experts (listed above) and review of literature from trade, business, and government organizations. While advanced manufacturing is viewed differently by different people, it probably should incorporate aspects of all the following perspectives when considering the public policy questions posed by PCAST.

Use of New Methods to Produce Newer or Better Products

Some experts define advanced manufacturing as a new way of the accomplishing the "how to" of production, where the emphasis is customization and scalability, while advancing the technologies necessary to improve capabilities. Paul Fowler of the National Council for Advanced Manufacturing (NACFAM) defines advanced manufacturing as an entity that:[1]

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[1] Discussion with Paul Fowler from the National Council for Advanced Manufacturing.

> Makes 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.

A similar definition was reported in a U.S. Department of Labor (DOL) Employment Training Administration (ETA) report, which defines "advanced manufacturing" as "implementing process improvements, increasing quality controls, and installing advanced robotics and other intelligent production systems."[2] Along the same lines, the Council on Competitiveness emphasized in its article "U.S. Manufacturing—Global Leadership Through Modeling and Simulation" that advanced manufacturing must entail high-performance computing (HPC) for modeling, simulation, and analysis.[3]

Manufacturing in New (as Distinct from Traditional) Industries

Others suggest a definition that remains broad in spectrum by not focusing on the use of particular technologies, but on manufacturing in new and emerging industries. A report by the New England Council and Deloitte Consulting [4] offers a definition that provides 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. Large volume product manufacturers (both process and fabrication industries) that compete traditionally by leveraging scale and low cost structures—and often include very advanced manufacturing technologies—would not be included in this definition as advanced manufacturers.

The Frontier of Advanced Manufacturing

Some experts indicated that making the above distinction between advanced manufacturing and traditional manufacturing is shortsighted, as technological advances and improvements in manufacturing occur in more mature or traditional industries as well as in emerging ones. They also challenged the notion of focusing advanced manufacturing solely on a particular set of technologies. In their view, advanced manufacturing was defined solely by advances that led to decreased cost or increased productivity. This definition applies to both existing products and new products being introduced into the marketplace in all industries.

Most discussants agree that an appropriate advanced manufacturing definition should be dynamic in nature be treated as more of a benchmark. That is, there is a constant iteration of improving manufacturing frontiers, which often are comprised of pre-commoditized processes and products. Therefore, what is classified as "frontier" is constantly changing, and, likewise, advanced manufacturing is always changing.

S&T-Based Manufacturing

A concise definition offered by some was that advanced manufacturing is manufacturing that entails rapid transfer of science and technology (S&T) into manufacturing processes and products. In today's globalized and information-rich environment, competitors can quickly and easily copy new products. Due to the speed of information exchange, the classification of cutting edge technology is dynamic and often seen as a moving target. To sustain operating on the cutting edge of innovation, it is crucial to reduce the time from research and development (R&D) to production. This definition is corroborated by a 2002 report by the National Defense University that defines

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[2] See *Advanced Manufacturing Industry*, U.S. Department of Labor, Employment and Training Administration, no date (circa 2004), available at http://www.doleta.gov/BRG/pdf/Advanced%20Manufacturing%20Report%2011.1.05.pdf.

[3] See "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.

[4] See "Reexamining Advanced Manufacturing in a Networked World: Prospects for a Resurgence in New England, New England Council, December 2009, available at http://newenglandcouncil.com/pdf/rep_webReports/rep_2010.01.14_AdvancedManufacturing.pdf.

advanced manufacturing as the insertion of new technology, improved processes, and management methods to improve the manufacturing of products.[5]

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[5] *Advanced Manufacturing Industry Study*, National Defense University, 2002.

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Question 1. What scientific and technical developments apply to a wide range of advanced manufacturing industries? What are the key advanced cutting-edge technologies, relevant across multiple industries that show the most potential for advanced manufacturing?

Introduction

There are clear indicators of a transformation in the production of goods that will usher in a new era of manufacturing. This new era derives from

- Scientific and technological developments that are pushing abilities to manipulate and consistently produce, especially at the molecular level
- Focused technological developments that enable sustainable manufacturing

This new era will draw upon and extend the revolution in microelectronics and the information technologies that employ them. Manufacturers will implement incipient abilities to consistently perform precise manipulation of materials at the molecular level, creating the emerging prospect of nanoscale manufacturing in which physics, chemistry, and biology converge. In addition, future technological developments will depend on a better understanding of fundamental biological processes and will apply these processes to a broad range of products beyond health. These developments are occurring in a highly connected and globalized marketplace where time to product and reduced production costs are crucial. Additionally, the sustainability of the production enterprise is becoming an explicit requirement for which new manufacturing approaches as well as improved information collection, analysis, and dissemination capabilities will be needed.

Convergence at the Molecular Level

The trend toward increasing interrelationship and convergence across traditional scientific disciplines is driven by the need to achieve new product characteristics. The drive to realize properties beyond those available in current products has pushed the frontiers of physics, chemistry, materials science, and biology and begun a convergence of these disciplines. This convergence is now leading to innovations at the molecular scale, at which new phenomena emerge and conventional rules no longer apply.

There is a vast difference between demonstrating a concept in a small sample and producing it in volume while still maintaining absolute control of the molecular composition, morphology, and properties. Working at the molecular scale requires analytical tools that analyze and simulate diverse processes with unprecedented scales of granularity, detail, fidelity, and complexity. Meeting these requirements demands sophisticated information processing capabilities for the integration of product design and production processes. It is also necessary to develop and implement real-time process controls for the highly precise execution of complex, interdependent processes. These new processes and controls will draw upon sensing and measurement that is well beyond the current state of the art.

The transition to fabrication of goods using processes at the molecular level is ushering a need to fundamentally improve upon the rigorous metrics and controls that the microelectronics industry introduced as it shrank dimensions to the nanometer scale. In that industry, the roadmaps produced through industry consensus and public-private partnerships enabled the equipment and materials supply chain to develop the appropriate materials, tools, and processes to continue product development at the rate of Moore’s Law.

This new era of manufacturing, however, faces a more daunting task than that faced by microelectronics. Not only must it extend manufacturing to nanoregimes, it must also bring together scientists and engineers from diverse disciplines with their different terminologies, methodologies, and processes to establish the technical basis for the manufacturing environment.

Implementation of novel technologies will vary by application, but the development of the technical capabilities to produce goods employing these technologies will build on crosscutting developments in tools, equipment, processes, and analytical capabilities.[1]

ISSUE: What should be the Federal Government's role in the development of production processes and related sensing, measurement, and analytical capabilities for molecular-level, atomically precise production.

Three example technology areas in which such capabilities are being developed are (1) next-generation optoelectronics; (2) structural materials based on nanocomposite materials; and (3) biomanufacturing. These areas represent the scientific and technical challenges that need to be addressed to realize the value of products based on next-generation manufacturing. Each of these areas is reviewed in Appendix 1-A to this paper.

Next-Generation Materials

Experts characterize advanced manufacturing as "new ways to manipulate and manufacture old materials or the processing of new materials for new applications." An example of this coupling is the innovative technique of using nanophosphate powder on the cathode of battery cells at A123 Systems. This material itself is not innovative, but the manufacturing process and application of this material is a novel way to make the battery more efficient and more competitive. Other examples of advanced materials include carbon nanotubes and advanced composites.

Creation of "metamaterials," artificial materials engineered to provide properties that may not be readily available in nature, was described as a goal of advanced manufacturing. These materials gain their properties from structure rather than composition, using the inclusion of small inhomogeneities to enact effective macroscopic behavior resulting in changes in novel characteristics such as a negative refractive index, electrical properties, or strength.

Potential applications of metamaterials allows for expansion of products in novel ways. For example, metamaterials have been used in photovoltaic materials in the form of a novel thin coating on the photovoltaic panel to increase possible installation environments such as deserts because the thin coating prevents sand particles from scratching the panels. Additional applications of metamaterials include high-resolution optical microscopes, data storage, nanocircuits for high-powered computers and superlenses that focus on objects too small to be seen with conventional optics.[2]

Innovative uses of both new and existing materials create opportunities for companies to develop niches and increase demand for their products, while increasing competitiveness by decreasing costs. Another example is the company 1366 Technologies that has recently received both ARPA-E and private venture funding. Using an approach of processing silicon in novel ways, 1366 Technologies plans to make the cost of solar power competitive with the cost of coal power.

Bioinspired Manufacturing Using Self-Assembly

Due to the advances at the molecular level, this new era of manufacturing faces a more daunting task than that faced by microelectronics. While the typical microprocessor integrates greater than a hundred million nanoscale electronic parts, miniaturized systems of the future will also need to incorporate photonic, mechanical, chemical, and even biological devices. Beyond the integrated circuit, there are developments to create multifunctional integrated systems that incorporate sensing, processing, and activation into increasingly small package sizes, but mass-manufacturing of such complex devices has proved challenging. Manufacturing processes to mass-produce useful multifunctional miniature systems have not yet been developed. Several researchers are looking to nature

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[1] *Productive Nanosystems: A Technology Roadmap*, Battelle Memorial Institute, 2007, discusses the many technology challenges entailed in developing and implementing atomically precise manufacturing.

[2] Kevin Bullis, "Superlenses and Smaller Computer Chips," *Technology Review*, March 2007.

and biological structures to solve this problem. Natural systems, with their complexity and sophistication, exceed what current microfabrication or nanofabrication techniques can currently achieve.[3]

The mass production using "biological machines" is a fundamentally new way of manufacturing because, in nature, components self-assemble to produce complex functional systems. The idea in the future of "growing" an integrated circuit or a biomedical sensor with advanced functionality and complexity may alter the approach to manufacturing at the micro- and nanoscale.

As an example, Angela Belcher and colleagues at MIT have harnessed the power of self-assembly to produce microscopic batteries that may be used to power small medical devices or labs on a chip. They used a virus called M13 to make the anode of the battery. The virus was genetically modified to generate structured arrays of cobalt oxide nanowires on top of a solid electrolyte. This was then assembled onto an etched silicon surface with thin bands of platinum and copper to complete the construction of the battery. [4]

New Applications of Three-Dimensional Printing

Three-dimensional (3D) printing to build prototypes and to aid new product development and realization is not an entirely new concept. However, 3D printing is now being applied to emerging fields such as tissue engineering and nanotechnology. Recently, two companies, Organovo and Invetech, have partnered together to build the first commercial 3D bioprinter to manufacture human tissues and organs. The technology originated from university-based research and holds the promise of one day being able to produce organs and replacement body parts on demand.[5]

A recent article describes 3D tissue structures such as myocardial patches being formed through the post-printing fusion of the bioink particles resembling the self-assembly phenomena in early morphogenesis.[6] 3D printing is also being employed to assist surgeons with difficult procedures and allow them to practice on realistic models built from 3D CT scan images. While 3D printers have been sold since the mid-1990s, the quality has significantly improved while costs have begun to come down. Z-Corp currently sells 3D printers ranging from $10,000 to $50,000, depending on size and sophistication. The company is working on building a product for less than $5,000. At such a price point, "Desktop Manufacturing" becomes much more achievable. Some believe through the combination of open innovation and tools such as 3D printers, entrepreneurs are poised to accelerate the pace of innovation. Other 3D printing applications include building models for prosthetics, creating prototype parts for robotics, and building architectural models.[7]

Sustainable Manufacturing

Sustainable manufacturing refers to the production of goods using processes and materials that are designed to minimize the product's environmental footprint. Sustainability goals include minimizing energy usage and materials waste, monitoring and reducing effluents, and mitigating other environmental impacts. Sustainability goes beyond the simple act of producing: it extends to the product's expected lifetime use and the complex system of components, energy, and transportation required to make the product and bring it to market.

Traditional approaches to reducing emissions have occurred at the point of emission—the tailpipe model. However, sustainable manufacturing is most fully realized when sustainability principles are applied at all steps of the design process, from material choice to waste stream minimization and management. The expansion of sustainability into the entirety of the product and production cycle will require innovative processes and thoughtful product design.

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[3] Babak Parviz, "The Future of Manufacturing," *Technology Review,* September/October 2007.

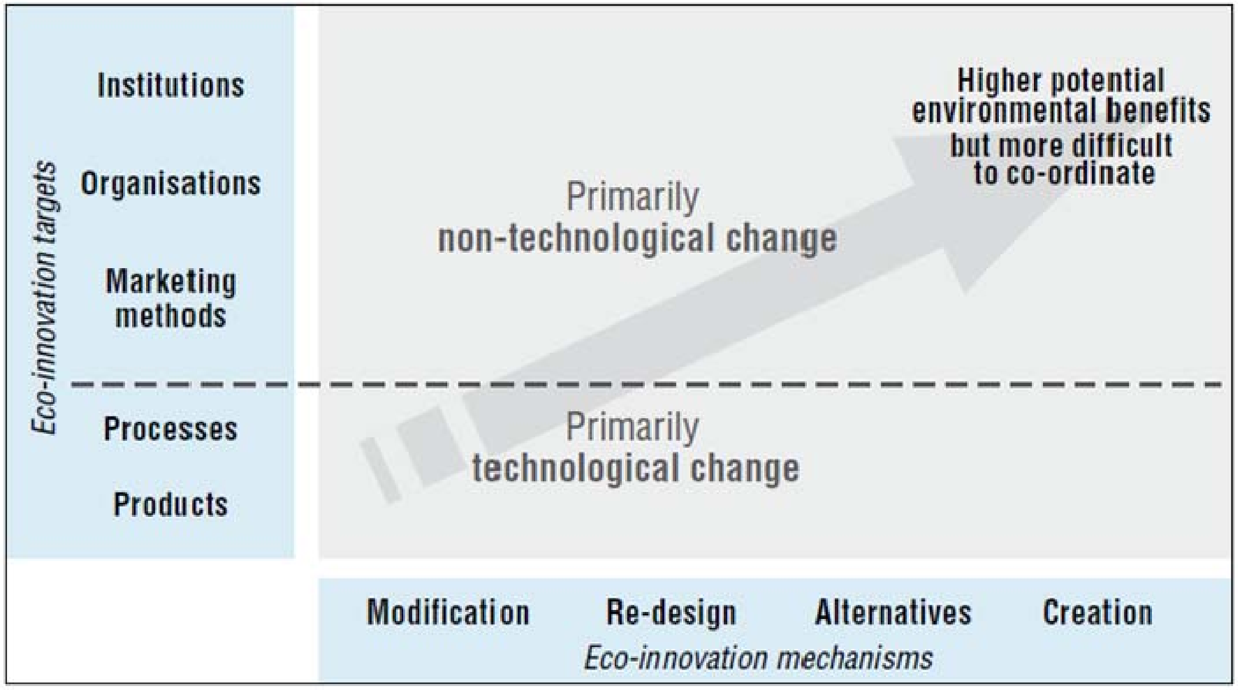
[4] Lauren Rugani, "Virus-Assembled Microbatteries," *Technology Review*, August 2008.

[5] Organovo Website: http://www.organovo.com/index.php

[6] Cyrille Norotte et al., "Scaffold-free vascular tissue engineering using bioprinting."*Biomaterial*s 30 (2009)

[7] Rachael King, "Printing in 3D Gets Practical," *Business Week,* October 2008

The OECD frames eco-innovation as a spectrum of novel processes, designs, organizations, and institutions that combine to have a positive impact on the environmental sustainability of a manufacturing process (see Figure 1-2). Among these innovations, changes in processes and products rely heavily on technological advances. These advances are likely to vary substantially from product to product; however, improved sustainability will draw on expertise from a variety of fields, including process management, mechanical engineering, and materials science.



Source: OECD Public Affairs Division (2009), "Sustainable Manufacturing and Eco-innovation: Towards a Green Economy," OECD Policy Briefs, June 2009.

Figure 1-1. Eco-innovation

Due to the complex production environment, sustainability requires the development of sophisticated product life cycle analysis tools so that environmental managers can track the footprint of a product throughout the distributed production system. It also requires data on processes and their effects, the collection of which is beyond the capability of most manufacturing firms today. Increasingly distributed manufacturing processes further complicate the assessment and management of progress toward sustainability goals.

While sustainable practices are often beneficial to the enterprise and can even reduce the cost of production, their development and implementation can entail considerable up-front costs and risks. Moreover, modifying a qualified manufacturing process may reduce yields or product performance in the short-term. Therefore, there may be a Federal Government role in developing and incentivizing the technological means for improving sustainability, especially insofar as they fall outside the direct interest and capabilities of individual firms and into the realm of social goods.[8]

ISSUE: Need for accessible and affordable measurement systems and analytical tools for assessing and managing sustainability across the production process

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[8] See "Sustainable Nanomanufacturing—Creating the Industries of the Future," National Nanotechnology Initiative Signature Initiative, NSTC Committee on Technology, Subcommittee on Nanoscale Science, Engineering, and Technology, February 2010, for a recent perspective on this role.

Conclusion on Key Science and Technology Challenges

Advanced manufacturing derives from advancements in technologies and operations across the production process. Some of these advances are in the actual forming of the product in terms of processes, tools, and equipment—at levels ranging from initial raw input materials, through parts and components, to their assembly into a final product. These advances are often specific to the specific end-product domain which can range from micro or even nanoscale devices (such as a planar complementary metal–oxide–semiconductor (CMOS) integrated circuit (IC) to large-scale integrated systems (such as a computer server that integrates multiple ICs with an array of additional electronic and electro-mechanical parts into a system or an aerospace system constructed of highly specialized structural materials with massive numbers of subsystems). The frontiers of product manufacturing are (1) advances needed to develop, employ, and integrate new materials and (2) advances in the ability to integrate parts and components more effectively and efficiently into intermediate and final products with increasing constraints on time-to-product, product cost, and sustainability, within a distributed value chain.

Appendix 1-A: Advanced Technology Manufacturing Frontiers

Integrated Optoelectronics

Photonics, also known as optoelectronics (OE), is that technology space where information signals carried by electrons are converted to photons and vice versa (O-E-O). Photons transport information in the form of amplitude, wavelength, and phase—or any combination of the above. Photonic devices are either active or passive. Passive devices merely transport the information-carrying photons from one location to another. Active components perform some function—convert electrons into light (lasers, displays), convert photons into electrons (charge coupled device sensors, avalanche photodiodes), merge streams of data-carrying photons (multiplexors), separate out merged streams of data-carrying photons (demultiplexors) and impart data on a stream of photons (modulators.)

The application of photonics covers such diverse areas as industrial lasers, consumer electronics, telecommunications, data storage, biotechnology, medicine, general illumination, and defense. Each of these application spaces has a supply chain and infrastructure that starts with basic materials and ends at a completed product. Along this chain are sub chains that provide the individual components or subsystems that make up the finished product.

A key dynamic in photonics is the evolution from discrete photonic devices to integrated systems. This integration is driven by the need for increased performance while simultaneously reducing cost and power consumption to meet the burgeoning demands for telecommunications and data communications—which themselves are becoming increasingly integrated.

Photonic Integration for Telecomm and Datacomm

Telecommunications networks and data centers that support the communications infrastructure and the Internet will require integrated photonics to meet demands that will overwhelm the massive switching centers that route the messages and data around the fiber optic network. These centers typically contain thousands of racks of electronic routers, in buildings that cover acres, and consume about 30 megawatts of electric power. As new mobile devices and internet video content increase the bandwidth capacity demand on the network, the service providers have to increase the number of channels carried by a single strand of optical fiber. Simply increasing the electronic content of a rack to accommodate increased bandwidth is not possible because of the associated increase in power consumption and heat dissipation. The solution lies in photonic integration.[9]

Photonic integrated circuits (PICs) combine multiple optic and electro-optic components onto a chip. Today's PIC technology is comparable to that of microelectronic large-scale integration (LSI) ICs of the 1960s—about 200 to 300 elements on a single chip. Most of the PICs today are hybrid—they consist of a silicon substrate with a number of monolithically integrated components, and a number of components fabricated from other materials mechanically, optically, and electronically connected to the substrate. PICs require components fabricated from other materials because silicon does not support a laser. Technologies and fabrication tools are needed that would support monolithic integration of silicon with other materials to enable PICs to move to higher levels of integration and take advantage of the existing silicon CMOS infrastructure.

The price of increased bandwidth is increased complexity and power consumption. The system requires more components to extract and groom the electrical signals from these increasingly complex optical signals and convert them into a form that electronic processors can manipulate. Each O-E-O requires many discrete, single-function optical components, including lasers, modulators, wavelength lockers, detectors, attenuators, wavelength division multiplexers (WDM) and de-multiplexers. In a typical optical transport system, each O-E-O conversion may require up to half a dozen optoelectronic or optical components, and a fully deployed 40-wavelength WDM terminal node may use upwards of 120 or more components interconnected by 260 or more fiber couplings. Each of these fiber couplings represents cost, signal losses, and a potential failure point.

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[9] Bikash Koley, "Network Architect at Google," presentation at the OIDA Photonic Integration Forum, October 6, 2009, Santa Clara, CA.

The industry sees the way to overcome this cost and complexity hurdle is through *photonic integration*. As such, three classes of devices represent the integration in the photonics world.

The planar lightwave circuit (PLC) consists only of passive devices fabricated from transparent materials using planar technology. It is essentially optical wiring and can perform some signal processing but does not alter the signal. Typically PLC materials are silica-on-silicon, polymers, and silicon on isolator (SOI). The industry has used this technology widely for the last 10 years.

The photonic integrated circuit (PIC) is the same as a PLC but also includes on-chip generation, modulation, alteration, and detection. It has both passive and active photonic devices (InP or GaAs-based) and transparent and opaque semiconductor materials with different band structures and doping. Semiconductor wafer processing technologies fabricate the optical waveguide devices. PICs can be monolithic, where all of the devices reside in one die, or hybrid, where certain devices are physically attached together onto a common platform to function as one unit. This technology represents the current state-of-the-art, and where industry R&D is focused.

The optoelectronic integrated circuit (OEIC) is the same as a PIC but includes on-chip electronics to drive the active elements and provide electrical outputs. It consists of photonic and electronic devices combined onto one chip and fabricated using semiconductor processing technologies. This future technology is one the industry hopes to achieve.

Because of the large existing infrastructure, silicon would be the ideal candidate for photonic integration. Although researchers have fabricated most of the required active and passive optical functions in silicon (Si), the fundamental challenge has been that silicon does not support a laser, an essential component in the optical world.

Academic and industrial researchers have devised clever approaches to mitigate this shortcoming of silicon. For the most part, they have relied on the indium phosphide (InP) materials system for the laser. The problem with InP is twofold—immature production environment and concomitantly the lack of a shared common production approach. First, the material and fabrication infrastructure is immature. Typical wafer sizes of InP are 3 inches, with leading edge at 6 inches. Silicon fabrication, on the other hand, typically uses 8- or 12-inch wafers. Six-inch technology for Si is many generations old. Because the market for InP devices is relatively small, the tool infrastructure has not benefited from a high level of investment. Second, InP devices have evolved in a manufacturing environment where the intellectual property is embedded in the process, rather than the design. As a result, one cannot take a device fabricated in one facility and replicate it using the processes of another fabrication facility (fab). Again, in this respect photonic integration is at the level of maturity of silicon in the 1960s, before CMOS became the technology of choice.

Notwithstanding the difficulties of monolithic integration on the InP platform, some companies, such as JDSU and Infinera, have successfully brought products based on monolithic InP integration to market. Oclero believes it is well-positioned for this market segment because of its InP fab in Caswell UK.

The second approach to PICs is to integrate as many passive and active components on a silicon substrate as possible, and then attach and couple critical non-Si components to the platform. One of the advantages of Si as a platform is that SiO_2 makes for an excellent waveguide material, and the processes can be fully compatible with the existing CMOS infrastructure. The challenge is in the mismatch of the thermal conductivities of InP and Si. As temperature changes, the components may shift slightly, impacting the alignment of the optical path. Companies that follow this approach include Kotura, Luxtera, and NeoPhotonics.

Potential roadblocks ahead include density limits, both on and off chip. With the massive amount of wire bonding required for these integrated photonic devices, and with all the wires running 10 or 40 GHz signals though them, they act like a phase antenna, bringing up serious issues of electromagnetic interference.

Another key impediment to PIC development is the lack of an economically viable foundry base. The economic reality is that many III-V foundries are struggling with excess capacity and no “killer application” in sight that would drive volume. Companies try to lock in what little customer base they have through proprietary processes that are not portable from foundry to foundry.

On the technical side, the lack of a robust market, has limited the development of comprehensive modeling software and other infrastructure elements. Researchers interested in building photonic integrated circuits have to either settle for excess die that foundries fabricated for some other application, or try to come up with a design that some foundry can then fabricate but with no guarantee that it will work as desired. Furthermore, the lack of software design tools and consistent qualified processes mean quick turnaround is not possible. Even if the initial dies work as desired, there is no guarantee that the dies fabricated on subsequent runs will have comparable performance.

The OEIC will require new techniques and tools for incorporating non-silicon materials into the CMOS process. The challenges are significant due to the differences in lattice constants, which cause threading dislocations, and differences in melting points of different materials. For example, the annealing temperature for the CMOS transistor source and drain, which is about 1000°C, is more than 50° above the melting point of germanium—the preferred material for a 40 Gbps avalanche gain photo detector. Notwithstanding these challenges, IBM has fabricated a transceiver completely in CMOS, including a fiber coupler, 6-channel WDM that is only 20 by 70 microns. Each channel connects to a 100-micron long modulator, which directly connects to the electronic driver and a detector that is only 10 microns long. The total device without a ring resonator assist is only 0.5 mm long; with a ring resonator, it is only 0.1 mm long.[10]

Nanocomposite Structural Materials

An area of growing importance is development of nano-enhanced advanced composites and related structures. Significant developments are underway in the industrial scale production of CNTs and incorporating CNTs within traditional constituent materials used to manufacture fiber reinforced PMCs.

CNTs are hollow cylinders that consist of individual or multiple walls of a graphite lattice structure. Multi-walled carbon nanotubes (MWCNTs) are generally easier to produce and less expensive to manufacture than single-walled carbon nanotubes (SWCNTs).[11] CNTs possess extraordinary tensile strength and exceptional stiffness. On a strength-to-weight basis, CNTs are unmatched by any other material. CNTs also possess especially high thermal conductivity and stability while some variants of CNTs possess especially high electrical conductivity and chemical resistance.

Fiber reinforced PMCs represent the largest and most diverse application for composites compared with those produced with metal, ceramic or other matrix materials. Applications for PMCs are highly diverse including sporting goods, aerospace defense, and automotive. While PMCs have been in use for decades, the introduction of nano-enhanced PMCs is a recent technological development which has large scale commercial potential of across virtually all major economic sectors (e.g., public works, heavy industry, energy production, power distribution, shipbuilding, consumer products, medical equipment, ground transportation, commercial aircraft, space and a host of military uses).

Carbon nanotubes are of relatively recent origin, with single-wall CNTs being discovered in the early 1990s and production processes developed since that time. Therefore large scale commercial use of CNTs in PMCs has been just getting underway over the last few years beginning with a small handful of applications. A number of companies are actively involved with incorporating CNTs in to various constituent materials that are used to manufacture PMCs. Nano-enhanced constituent materials can significantly improve the material properties of PMCs and attendant structures (e.g., higher strength and lighter weight) by leveraging the extraordinary properties of CNTs. Examples of the types of PMC constituent materials that can be enhanced by CNTs include thermoplastic and thermoset resins, adhesives and resin infused textiles (known as “prepregs”) that are subsequently fabricated into laminated and other PMC structures. Additional approaches to nano-enhanced PMCs includes incorporating CNTs into the manufacture of existing fibers are used to reinforce PMCs as well as developing entirely alternative forms of new fibers produced from CNTs.

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[10] Yuri Vlasov, IBM Research, “Transition from telecomm to datacomm to computercomm,” OIDA Photonic Integration Forum, October 6, 2009, Santa Clara, CA.

[11] SWCNT have a diameter on the order of1 to 3 nanometers (nm) while the diameter of a MWCNT can average from 8 to 10 nms. The individual wall thickness of CNTs measures an atom thick and the length of CNTs can reach several millimeters (mm).

Nano-enhanced PMCs stand to revolutionize advanced composites by enabling the development and manufacture of PMCs with heretofore unheard of properties without the traditional tradeoff of material performance (e.g., increasing material strength without sacrificing weight reduction). The amount of CNTs added to PMCs to achieve optimal levels of higher performance can range from 1 to 3 percent by volume. In addition, CNT producers claim that the added performance to PMCs provided by their products can be achieved at a relatively low cost and may only increase the price of constituent prepreg material by 7 to 10 percent. However, the cost of CNTs is not cheap, on the order of $45 per pound. Nano-enhanced PMCs are anticipated to also spur the development of new classes of composites including multi-functional materials (e.g., smart, adaptive and self-healing structures).

For use in composites the main technical challenges are not the nanotubes themselves.[12] While commercial scale production of CNTs is relatively new, there is already considerable CNT production capacity in-place. For example, as of January 2010, there exists single firm annual production capacity of over 200 metric tonnes (MTs), and single firm annual capacity is projected to increase to 400 MTs before the end of 2010.

However, large-scale use of CNTs in PMCs is still in the early stages of development and faces significant technical obstacles. The greatest barrier to integrating CNTs into manufacturing PMC constituent materials and associated downstream composite structures is the lack of needed processing technologies, expertise and knowhow. Examples include the natural tendency of CNTs to reagglormerate in resin and prepreg, which subsequently impairs homogeneous dispersion of nanomaterials and resin viscosity. The inability to effectively control uniform dispersion of CNTs in composites processing can result in failure to maintain desired material property values of finished PMC structures (e.g., strength, stiffness and toughness). Other barriers confronting wider scale use of nano-enhanced PMCs (and CNTs more generally) includes environmental, health and safety concerns as well as the lack of material standards, reference data and design tools. There are alternative approaches in development for employing CNTs in manufacturing PMCs, such as those being developed by Nanocomp, that are expressly aimed at overcoming these obstacles.

Nano-enhanced PMCs are nevertheless currently being commercialized for diverse uses in consumer products (e.g., sporting goods and cases for laptop computers), renewable energy (e.g., windmill blades) and limited ground transportation applications (e.g., automotive parts). However problems associated with effectively integrating CNTs within existing PMC manufacturing processes need to be overcome if nano-enhanced PMCs are to be more widely accepted into increasingly more demanding applications such as aerostructures used in commercial aviation, military aircraft and other high consequence uses.

Biomanufacturing

Biomanufacturing at its broadest definition can be understood as encompassing all activities that either utilize biological processes to create products (that can be biological or non-biological) and/or have as their main product a biological substance. Products that can be made via biomanufacturing include pharmaceuticals, fuels, food, nutraceuticals, biomaterials, and even inorganic substances.[13] Processes that can be considered under biomanufacturing include using “native” biological expression systems, or altering those systems using genetic engineering, metabolic engineering, and the principles of synthetic biology more broadly. Currently, biomanufacturing is most readily identified with the production of biopharmaceuticals—the process by which they are fermented, purified, and packaged and distributed to the end customer—yet there are emerging areas of biomanufacturing that deserve attention and are briefly mentioned below.

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[12] The production constraints for CNTs for composites are less demanding than those for such applications as electronics, for which the performance characteristic are more exacting.

[13] For example, Dr. Belcher at MIT has genetically engineered viruses to attract inorganic materials to their outer shell to form nanowires, batteries, and other devices. “Researchers Build Tiny Batteries with Viruses,” MIT News, April 2006, available at http://web.mit.edu/newsoffice/2006/virus-battery.html.

Biopharmaceuticals

The United States is considered the global leader in manufacturing biopharmaceuticals, and it currently benefits from a large "installed base"—for it takes 5-8 years and from $500 million to $1 billion to design, build, and license a biomanufacturing facility. Yet biopharmaceutical production facilities (including contract manufacturing organizations) have begun to move offshore, with facilities operating in Singapore, Puerto Rico, South Korea, and India. Other countries have large-scale initiatives to attract biomanufacturing to their countries, including the United Kingdom's National Biomanufacturing Centre. Some industry leaders believe that the U.S. biomanufacturing industry is at the stage that the semiconductor industry was in the late 1980s when SEMATECH and other public-private partnerships were developed to revitalize the capacity to manufacture integrated circuits with the United States. Small-scale government-academic-industry partnerships, such as UC Berkeley's Center for Bioprocess Operations and MIT's Center for Biomedical Innovation, and the NSF-funded Northeast Biomanufacturing Center and Collaborative (NBC2), have been developed to support biomanufacturing within the United States.

Several challenges in biopharmaceutical manufacturing include:

- Optimizing expression systems—production based on living organisms is variable and can be improved
- Improving product and process characterization
- Streamlining plant design and operations—as the capital investment for plants is large and has to be done in advance of demand (there are costs for building too early—idle capacity—as well as for being too late—lost sales)
- Strict regulatory environment requirements for process validation and Certified Good Manufacturing Practices (CGMP)—and changing regulatory requirements
- Workforce shortage

Tissue Engineering

Another more recently developed type of biomanufacturing is what is often referred to as "tissue engineering"—this area can include the related field of "regenerative medicine" based on the use of stem cells. Tissue engineering is primarily focused on the creation of complex biological materials, including bones and organs. The U.S. Federal R&D community has provided substantial funding for tissue engineering. These activities are coordinated through the Multi-Agency Tissue Engineering Science (MATES) Interagency Working Group. MATES defines tissue science and engineering as "the use of physical, chemical, biological, and engineering processes to control and direct the aggregate behavior of cells."[14] Some observers believe that this may be a future area of manufacturing in the United States, although there remains much basic research needed on these areas. To date, no programs have been identified that specifically focus on the scale up and development of processes that have been shown to work at the lab scale. However, scale up is a stated priority of the MATES group in their 2007 strategic plan.[15] Although several companies exist in this area, no large-scale revenues have yet been attained. The first commercial 3D bioprinter, able to print skin, muscle, and short stretches of blood vessels, will soon be released to researchers.[16]

Synthetic Biology

Another area that may have impact on the future of biomanufacturing is genetic engineering or, when considered as a part of an overarching framework, "synthetic biology." Ad-hoc genetic engineering has been in use for several decades; the first use of genetically modified *E. coli* to manufacture synthetic human insulin occurred in 1978. But the advancement of DNA sequencing and related understanding of gene and protein functions has made this area

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[14] Multi-Agency Tissue Engineering Science (MATES), http://www.tissueengineering.gov/.

[15] *Advancing Tissue Engineering Science and Engineering: A Multi-Agency Strategic Plan*, Washington, D.C., Executive Office of the President, June 2007, http://www.tissueengineering.gov/advancing_tissue_science_&_engineering.pdf.

[16] "Making a Bit of Me: A Machine to Print Organs is Coming to Market," *The Economist,* February 18, 2010, available at http://www.economist.com/science-technology/displaystory.cfm?story_id=15543683.

ripe for exploration. Recent research shows that green algae and genetically modified yeast can produce proteins more cheaply than traditional systems,[17] and that the Tobacco Mosaic Virus can be engineered to rapidly produce a vaccine for the quickly-shifting norovirus.[18] Several government programs have been established to support this type of research, including DARPA's Accelerated Manufacture of Pharmaceuticals (AMP), DOE's Joint Bioenergy Institute, and NSF's Synthetic Biology Engineering Research Center (SynBERC).[19]

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[17] Amber Dance, "From Pond Scum to Pharmacy Shelf" *Nature Medicine*, vol 16 No 2, 010, pp. 146–149. http://www.nature.com/nm/journal/v16/n2/full/nm0210-146.html.

[18] "Tobacco plants yield the first vaccine for the dreaded "cruise ship virus, " American Chemical Society, press release, August 18, 2009, available at http://portal.acs.org/portal/acs/corg/content?_nfpb=true&_pageLabel=PP_ARTICLEMAIN&node_id=222&content_id=CNBP_022762&use_sec=true&sec_url_var=region1&__uuid=3f4c6a40-bad2-4959-8547-3fdc85dacf49.

[19] "Could Mini Labs and Plant-Based Vaccines Stop the Next Pandemic?" *Scientific American*, March 1, 2010 . http://www.scientificamerican.com/article.cfm?id=h1n1-plant-vaccine.

Question 2: What are some possible new concepts of advanced manufacturing that might apply to a wide range of industries?

Many believe that in today's world, manufacturing advances will derive from information and integrated production technologies that create new capabilities to rapidly and efficiently design and produce products economically. Beyond the production of specific products, captured in the term "product realization," manufacturing is an element of a larger enterprise that entails product conceptualization on the one end and product delivery through sales on the other. The integration of manufacturing with the design and delivery processes is itself a frontier stressing data collection, dissemination, and processing capabilities and analytic tools and processes for rapidly making decisions on complex issues. Other concepts—such as open innovation and "cloud producing"—enable the leveraging of collective intelligence and feedback through the use of internet technologies.

Distributed, Rapidly Responsive, Complex Product Realization

"Complex product realization" refers to the technologies and processes associated with conceiving, designing, and manufacturing highly integrated, multi-component systems.[1] Complex product realization is enabled by a confluence of radical advances in information technologies, analytical tools, and the changes in organizations these advances will enable. In this approach, sophisticated simulations are seamlessly integrated with conceptual and detailed design tools. These tools can allow customers, designers and product managers to learn and adapt together as they experiment in real time with a multitude of product concepts. Intelligent agents monitor the process and provide guidance on overall design strategy, technical risks and opportunities, manufacturing issues, reliability, and life-cycle cost.

The foundation of this product realization environment is improving information technologies—i.e., the convergence of digital technologies for voice, data, and images, combined with increasing processing power, network capacity, and software efficiency. Much of current research aims to leverage emerging information technologies to coordinate the activities of design teams, managers, and supply chain players as to reduce product cycle time and life-cycle cost while increasing user satisfaction with the resulting products. Sophisticated, network-based design tools that facilitate concurrent optimization of component and subsystem designs are already being used in some product areas and are expected to diffuse widely over the next decade.

The results of these designs as products require their integration with automatic, flexible manufacturing technologies. Push-button production of individual machined parts from completed computer-aided design (CAD) definitions is already a reality: numerically controlled machine programs can be generated directly from CAD definitions, downloaded into the machines, and immediately utilized to cut metal and form the part. Analogs exist for cast and molded parts and deposition processes. The CAD program generates a definition of the mold, die, or master from the part definition and programs the code to machine the mold or master, then the mold or master is made and the part is cast. Several shops now use automatic, CAD-based manufacturing as their basic method. Conceivably, this automatic manufacturing approach renders obsolete traditional notions of a learning curve. Design organizations seek to exploit "learning in manufacturing process simulation" before any metal is cut.

Versatile mills and lathes now can machine to such accuracy that many finishing steps are eliminated. Various other applications of information technology are being used to automate other aspects of the manufacturing process (e.g., material handling, part tracking, and equipment maintenance), enable on-line problem diagnosis, and provide self-correcting capabilities at the enterprise level. These applications will allow for real-time tracking of manufacturing flows across the enterprise, making current "batch and queue" operations more like continuous

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[1] Richard Van Atta, et al., *Complex Product Realization 2020: Key Issue Areas*, Institute for Defense Analyses, December 15, 1999.

process control situations. The ultimate result could be single setup tool-less manufacturing that is economically efficient, but not based on the need for economies of scale of traditional machining.

Single-unit manufacturing should be especially advantageous to weapon systems and other “high-end” products that are generally built in small volumes relative to commercial products and are built at low rates in an environment where needs change rapidly. Single-unit manufacturing could facilitate rapid reconfiguration of a design to accommodate changes in the requirements, followed by a quick small production run of the modified system. Such a change warrants a fundamental re-thinking of how parts are designed, since part by part customization would become much more practical than before. Replacing complex, assembled units with large machined castings may be more attractive than before.

To realize this perspective, a set of overlapping challenges will need to be addressed:

- *Logic of knowledge abstraction:* There is a need for product definition capabilities that can represent the product in fine detail for parts designers, less detail for systems engineers, and even less detail for the chief engineer’s perspective. Research areas include data structures and intelligent agents.
- *Distributed, Adaptive Algorithms for Optimization of Multi-Dimensional Designs:* The different levels of the design space result in tradeoff problems that tend to be discontinuous and ill conditioned. This suggests that there may be mathematical properties that are characteristic of these spaces, and that search algorithms might be created that could exploit these characteristics to yield more optimal and more robust solutions. Research areas include visualization technology and, again, intelligent agents.
- *Mathematics and Science of Product Architecture and Modularity:* The interconnection of design challenges means that complex product realization will increasingly involve integrating “system of systems.” To do so, it will be important to identify interdependent risk drivers and manage total risk posture across entire platforms and across time. Key areas include representing and valuing flexibility, structuring supply chains, and cost modeling.
- *Virtual Characterization and Qualification of “System of Systems” Products and Processes:* The physical models that underlie current product realization systems will need to keep up with new technologies, which frequently exceed customary operating regimes. Emerging technologies such as microelectromechanical systems (MEMS), biomechatronics, and nanotechnology will require entirely new manufacturing processes and process characterizations.

Increasingly powerful computers, readily accessible high-speed networks, and even social media can provide nearly instantaneous information on product requirements, characteristics, and performance throughout the “value chain” from product concept to final production. This can facilitate, but also create increasing demand for, more rapid information and responsiveness throughout the increasingly distributed production system both within and amongst firms.

Distributed supply and production can lead to more granular, modular, flexible, adaptive, and, hence, responsive production. To be effective, these information systems must be capable of capturing data from multiple sources, and transmitting them across the system in usable formats. If properly implemented, such a system can match customer demands to supplier availability to production capacity and deliver the product on schedule—by providing information on precisely what is needed when it is needed.

ISSUE: Development and integration of the underlying analytical capabilities (algorithms, mathematical representations, logic structure, etc.) for use by enterprises in highly responsive, distributed production.

In addition, distributed production of complex components and subsystems with tight tolerances stress suppliers’ ability to manage and control processes and equipment. External factors such as temperature, humidity, and starting material composition and morphology all can affect the quality of the end product. Internal factors, such as machine calibration, component wear, setup, and operation parameters are likewise important. Both environments change over time, affecting tolerances and equipment performance. This highlights the need to develop processes that can be measured and controlled *in situ* and in real time. These high-performance production tools must also be affordable for suppliers in a distributed production system.

As system manufacturers require ever-tighter tolerances, machining has to transform from being an operation to a *process*. To maintain tolerance and uniformity of product, the machinist must know *in real time* the temperature of the work piece, the temperature of the tool head, the temperature of the cooling fluid, the viscosity of the coolant, the coolant flow rate, the feed rate, the wear on the tool head, among other parameters. To achieve real-time monitoring, an information infrastructure, with integrated sensors, based on validated models and simulations has to be developed. In effect, the machining operation has to follow the path of the semiconductor industry by focusing on qualified processes and minimizing human intervention. As one machine shop proprietor stated, “We have to move from *man*ufacturing to *auto*facturing.”[2]

Machine shops are a vital element of the manufacturing infrastructure. Most manufacturers of complex systems no longer support an in-house machining operation. Rather, they outsource to specialty machine shops who fabricate components to their specifications. In the United States, most manufacturers rely on the approximately 22,000 machine shops, which have combined annual revenues of $30 billion. The industry is highly fragmented with no major companies, and the 50 largest generate about 15 percent of the total revenue. Only a few hundred operations have more than 100 employees.[3] As such, they are in no position to develop sophisticated flexible manufacturing processes.

ISSUE: Affordability of advanced high-performance manufacturing tools, equipment, and processes for use by enterprises for distributed, responsive production.

Leveraging Modeling and Simulation

Traditionally, creating the scientific insight needed to address manufacturing issues has been done through methods that rely heavily on testing and demonstration. While this approach has been very successful, it takes a long time and is expensive. Over the past 15 years, a new capability has been added to theory and experimentation to create scientific insight about complex physical systems. With the advent of very high-powered computing, advanced modeling and simulation that is full-dimensional, high-resolution, and based on first principals has proved invaluable for delivering faster and more detailed insights into the operation of physical systems.

An example is the modeling and simulation center created by the Department of Energy Office of Nuclear Energy (NE).[4] The NE Modeling and Simulation Hub will utilize advanced modeling and simulation capabilities (e.g., computational fluid dynamics) through a new multi-physics computational capability that will provide predictive capability for life extension and power uprate calculations. After 5 years, the Hub is intended to produce a multi-physics computational environment that can be used by a wide range of practitioners to conduct predictive calculations of the performance of reactors in the future for both normal and off-normal conditions. The Hub creates a user environment that allows engineers to create a simulation of a currently operating reactor that will act as a “virtual model” of that reactor. The Hub will also obtain data from that reactor to be used to validate the virtual model. In turn, engineers will use the virtual model to address important questions about the operations of and safety basis for the physical reactor. Finally, the combination of the virtual model and the physical reactor will be used to (1) communicate the potential role of science-based modeling and simulation to address nuclear energy technology issues in the near, mid-, and long terms and (2) aid with the design and manufacture of next-generation nuclear power plants. The first award for the NE Modeling and Simulation Hub is expected to be awarded in June 2010.

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[2] Personal interview with machine shop proprietor.

[3] First Research Corporation, *Machine Shops*, updated November16, 2009.

[4] See http://www.energy.gov/hubs/modeling_simulation_nuclear_reactors.htm.

Mass Customization

One of the definitions of advanced manufacturing references the need for new manufacturing platforms to be flexible to respond to customer demands. An emerging advanced manufacturing concept suggested in discussions with experts is the ability to achieve cost-effective "mass customization" of a product. Through advances in complex product realization and single-unit manufacturing, as described previously, mass customization is becoming a more plausible reality. Advanced manufacturing techniques, such as solid free-form fabrication (often called "additive manufacturing") and laser processing, can create complex, custom products and replacement parts that are required to be produced quickly in low volumes.[5]

Such advances in manufacturing could lead to new ways of approaching personalized medicine and biomanufacturing of pharmaceuticals. Some define personalized medicine as "a form of medicine that uses information about a person's genes, proteins, and environment to prevent, diagnose, and treat disease."[6] Given limitations and reduced efficacy of conventional medicines across broad patient populations, many researchers are looking towards personalized healthcare strategies and cell-based therapies to better target diseases. However, manufacturing technologies for targeted therapies that meet the regulatory and economic requirements for successful commercialization are still in embryonic stages.

Another example of mass customization that emerged from discussions with industry experts is the manufacturing of customizable prescription eye lenses with unique features. The technology, developed by Luxottica, allows for special features such as coatings and progressive lenses to be made more precisely through new layering technologies. Advances in manufacturing processes to create desktop machines have enabled the company to automate lens manufacturing for improved quality at a lower cost.

Open Innovation Manufacturing

Another emerging concept leverages the power of collective intelligence and information technology to collect new design and manufacturing strategies for product development. A recent article describes a Boston-based Company, Local Motors Inc., as the first open-source automotive company.[7] Local Motors aims to build an off-road, but street-legal, vehicle to be released in June 2010. Through a Creative Commons license,[8] not only design ideas but also development and manufacturing solutions (most of which were off-the-shelf components) were solicited from the public. Through well-managed community input as well as technologies such as 3-D design software and photorealistic rendering technology, enthusiasts and Local Motors employees worked together to design and build a car that, according to the article, "puts Detroit to shame."

Network-Centric Manufacturing

A recent report, *Rationales and Mechanisms for Revitalizing U.S. R&D Manufacturing Strategies,* argues that a major requirement for competitiveness in manufacturing is a greater use of information technology to more effectively integrate all business operations in manufacturing supply chains. One method of achieving this goal is through network-Centric manufacturing (NCM), defined as: [9]

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[5] Greg Tassey, "Rationales and mechanisms for revitalizing US manufacturing R&D strategies," *Journal of Technology Transfer,* published online 29 Jan 2010, available at http://www.springerlink.com/content/e70574777627wmg4/fulltext.pdf.

[6] See National Cancer Institute, "Definition of Terms," available at http://www.cancer.gov/templates/db_alpha.aspx?CdrID=561717.

[7] Chris Anderson, "In the Next Industrial Revolution, Atoms Are the New Bits," *Wired Magazine*, January 25, 2010.

[8] Creative Commons is a nonprofit organization that works to increase the amount of creativity (cultural, educational, and scientific content) in "the commons"—the body of work that is available to the public for free and legal sharing, use, repurposing, and remixing.

[9] Kenneth Saban and John Mawhinney, "The Importance of a Balanced Framework in Network Centric Manufacturing," DSN Innovations, available at http://www.dsninnovations.org/docs/pdf/Importance_of_Balanced_Framework_in_NCM.pdf.

> …the gathering of geographically dispersed organizations via the Internet and information technologies to fulfill a specific business goal. Such organizations—like Dell, Cisco, Boeing, IBM, and Nike—act more as designers and system integrators, with a larger percent of manufacturing being done by various manufacturers in their supply chains.

NCM manages the manufacture of products throughout their life cycles within an enterprise in which agile partners exploit new capabilities in connectivity, new skills in collaboration, and new strategies for network visibility.[10]

Toward "Cloud Producing"

One example of NCM was presented in a recent *Science* magazine article by Lewis Branscomb. Branscomb describes a Chinese apparel manufacturer (Li & Fung, a Chinese global sourcing firm) that addressed their low-margin problem with an approach they describe as "process orchestrator".[11] The company does not own equipment, but by focusing on logistics, they define and customize the production process. They work with over 12,000 suppliers in more than 40 countries, yet they retain only about 14,000 employees of their own. [12] Their relationship with partner firms is based on the "30/30" principle: Li & Fung will commit to purchasing at least 30 percent from a partner but will not exceed 70 percent capacity of that firm. This ensures that the partner firm is viewed as significant, but they still must go outside the network to survive. The result is that each firm is specialized and must be able to innovate—to take on new ideas, new varieties of skills, and new products. The asset productivity of this arrangement for Li & Fung is very profitable. They optimize on the collective innovative capacity of their partners needed for a specific product by orchestrating them into a flexible, agile, and skilled collaborative supply chain.

Final Thoughts

The new concepts listed above emerged from our review of the literature and interviews conducted with about a dozen experts from academia and industry. While these experts gave examples of different new concepts and many of them are discussed above, one insight that came from most is that there is no technology "silver bullet" that will resuscitate manufacturing in the United States. The experts warned us that while investing in S&T is important, it may be beneficial to stay away from "buzzword" advances like "instant manufacturing," among others. The advice given was that it is more important to incorporate incremental but systemic changes to the manufacturing enterprise. This includes investing in early stage technology development, improving the flows of knowledge across interfaces (for example, through improved public private partnerships), better training of students to prepare them for global manufacturing jobs, and better understanding and integration of customer, manufacturing, and sustainability needs at the design phase. While these concepts are not necessarily glamorous, they are what the experts believe will create value in the manufacturing enterprise.

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[10] Bill Kessler, Eric Mittlestadt and Jack Russell, *Infrastructure in the Possible Futures of Network-Centric Manufacturing*, NACFAM Report, June 2007 http://www.nacfam.org/Portals/0/NACFAM%20Misc% 20Files/NCMThoughtPaper.pdf.

[11] Lewis M. Branscomb, "Research Alone Is Not Enough," Science, Vol 321, August 15, 2008, available at https://www.sciencemag.org/cgi/reprint/321/5891/915.pdf.

[12] Li & Fung Limited Web site: http://www.lifung.com/eng/global/home.php.

Question 3: What is the appropriate role of Government science and technology programs and policies in advanced manufacturing?

The net value of goods produced by manufacturing steadily increased since the end of World War II, but this growth appears to have stalled in the most recent decade. Employment statistics reinforce this picture, showing associated reductions in employment, which do not appear to follow the recovery trends of previous business cycles. U.S. manufacturing employment peaked in 1979, and employment levels have fallen by 30 percent in the past decade. When trade of manufactured goods with other countries is factored in, relative competitiveness appears to be in decline as well. In 2008, for example, the trade deficit for manufactured products, including advanced technology products, was $500 billion.[i]

In the early part of the past decade, the decline of the manufacturing sector was seen as a natural evolution from an industrial to a post-industrial society, and according to some experts,[1] even a post-scientific society, with parallels made to declining employment in and increasing productivity of the agriculture sector at the beginning of the twentieth century. While calls for maintaining a vibrant manufacturing base have been made periodically,[2] others recommended focusing on the growing service sector.

In the aftermath of the financial and real-estate sector busts, many experts and policymakers are once again looking to manufacturing as a new source of growth and jobs. The primary reasons offered are related to economic strength and national security as expressed in the recent writings of Pisano and Shih,[3] Gomory,[4] and Tassey.[5] These experts emphasize that the manufacturing sector produces wealth through exports, and provides jobs not only to those working in the manufacturing sector directly but also in other sectors, through the ripple effect on the economy in general.[ii] In the defense sector especially, manufacturing is seen as a key strategic asset.[iii] With the ascent of manufacturing in other nations, both as a result of offshoring activities and other countries' domestic policies, concerns about overall loss of competitiveness have been raised as well. Some observers contend that as manufacturing is offshored, research and development, which is tightly linked with manufacturing, will follow, and loss of the research base is viewed by the same observers as a critical loss for the U.S. economy. Although there are those who believe this contention is immaterial,[6] there seems to be near unanimity among policy experts that something needs to be done. The challenge now is to agree on what needs to be done and by whom.

The U.S. private sector has operated largely on free-market principles in a globalized economy, with the U.S. Government playing a role primarily in strategic areas linked to the defense enterprise. Given the comparative advantages offered by some countries, such as China, in the latter part of the twentieth century, private sector firms began offshoring low-end manufacturing activities.[iv] Proponents of globalization believe that this shift was inevitable and likely to continue in one form or another, and that it is ill-advised to erect protectionist walls, or force U.S. firms to "bring jobs back."[7]

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[1] Christopher Hill, "The Post-Scientific Society," *Issues in Science and Technology,* 24, 78 (2007).

[2] Manufacturing in America: A Comprehensive Strategy to Address the Challenges to US Manufacturers, Department of Commerce, 2004.

[3] Gary Pisano and Willy Shih, "Restoring American Competitiveness," *Harvard Business Review*, July-August 2009.

[4] Ralph Gomory on Manufacturing, available at http://www.athenaalliance.org/weblog/archives/2009/07/ralph_gomory_on_manufacturing.html, accessed March 4, 2010.

[5] Greg Tassey, "Rationales and mechanisms for revitalizing US manufacturing R&D strategies," *Journal of Technology Transfer*, DOI 10.1007/s10961-009-9150-2.

[6] Amar Bhide, *The Venturesome Economy: How Innovation Sustains Prosperity in a More Connected World, 2008.*

[7] See *Manufacturing Industry*, National Defense University,2009; Robert Reich, *The Future of Manufacturing, GM, and American Workers (Part I),* http://robertreich.blogspot.com/2009/05/future-of-manufacturing-gm-and-american.html, accessed March 8, 2010; *How to Compete and Grow: A Sector Guide to Policy*, McKinsey Global Institute, available at

Both policy experts and policymakers (see, e.g., White House Framework for Revitalizing American Manufacturing 2009[8]) contend that instead of competing with other nations on low cost and "racing to the bottom," the United States should shift its manufacturing focus, and concentrate on those manufacturing activities that generate high value, provide high wages,[v] are environmentally sustainable, and not likely to be easily duplicated by other nations or off-shored in the near future (collectively referred to as Advanced Manufacturing).

Advanced manufacturing requires high and sustained levels of support for breakthrough advances—not just in science and technology (S&T), but also in areas such as production process development and maturity, business process innovation, and worker training. Advocates argue that the Government needs to provide this support, citing three primary reasons. Each is rooted in the economic argument related to market failure.[vi]

Low Likelihood of the Private Sector Investing in Breakthroughs Supporting Advanced Manufacturing (the "Public Goods" Argument)

Many of the breakthroughs related to advanced manufacturing are likely to come from S&T; however, firms typically do not invest in S&T.

- Return on investment on frontier research—the type of research needed for advanced manufacturing—is uncertain, and fraught with technical or market related risks; furthermore, this return has a longer time horizon than acceptable to firms' shareholders.
- Firms' system boundaries are around their worldwide enterprise, not nations—loss of employment in the home countries is less worrisome than loss of shareholder value. Firms (especially large ones that have large markets overseas) think of themselves as global enterprises, and job creation, even in home countries, is typically not a major priority.
- As private sector profit margins shrink, and there is less access to outside capital (e.g., bank loans), even firms interested in innovating are less able to invest in acquisition of emerging S&T (directly or through sponsorship of research at universities).
- Many enterprises, especially small and medium sized, are not adequately linked to the knowledge network to participate in research to push the frontiers of science or translate them into applications, nor learn about emerging technologies.

If the private sector cannot or will not make the investment in the research base but it needs to be made, the Government must, the argument goes, take a lead in making this investment. The rationale here is identical to the one made for why the Government must invest in basic research: that any returns created by this activity are long term, sometimes not marketable, and not always evident (Kenneth Arrow spoke of "indivisibilities,[vii] inappropriability, and uncertainty"). Yet the rate of return to society as a whole generated by investments in research is significantly larger than the benefits that can be captured by the firm doing the work. Research is therefore is a *public good* to be supported by public funds. [viii,9]

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http://www.mckinsey.com/mgi/reports/freepass_pdfs/competitiveness/Full_Report_Competitiveness.pdf, accessed March 8, 2010.

[8] A Framework for Revitalizing American Manufacturing, December 2009, available at http://www.whitehouse.gov/sites/default/files/microsites/20091216-maunfacturing-framework.pdf, accessed February 6, 2010.

[9] Experts who have written on the topic include: Kenneth Arrow, *Economic Welfare and the Allocation of Resources for Innovation*, 1962. Edwin Mansfield, "Social Returns From R&D: Findings, Methods, and Limitations," *Research/Technology Management*, November-December 1991, 24. Charles I. Jones and John C. Williams, "Measuring the Social Return to R&D," *Quarterly Journal of Economics*, November 1998, 1119. Richard R. Nelson and Paul M. Romer, "Science, Economic Growth, and Public Policy", in Bruce R. Smith and Claude E. Barfield, eds. *Technology, R&D, and the Economy*, (Washington, The Brookings Institution and the American Enterprise Institute, Washington, 1996).

Low Likelihood of the Private Sector to Invest in Environmentally Responsible Manufacturing (the Public Goods and Negative "Externalities"[ix] Arguments)

Environmental trade-offs in advanced manufacturing are complex, and difficult to make at the enterprise level, since firms typically do not account for market externalities. For example, next generation lightweight composites instead of steel addresses the fuel efficiency problem, but creates others—composite materials increase waste because they are currently not recyclable, and have no feasible recycling technologies on the horizon. As a result, firms are likely to ignore the cost of environmental remediation of their activities, thus creating a role for Government both from the point of view of regulating—correcting for negative externalities—but also supporting research in "sustainable manufacturing"—a *public good* as discussion in the section above.

Some aspects of advanced manufacturing are energy intensive. Industry accounts for about a third of the total energy use in the United States, and manufacturing is responsible for around 80 percent of industrial use. In addition, the manufacturing industry designs and builds all of the equipment used in the other major energy use sectors. Reducing energy intensity is essential not only to firms as they try to minimize their cost of production but also in achieving national energy and carbon dioxide reduction goals.

Manufacturing also creates pollutants and is resource intensive. Both attributes, as Table 3-1 shows, have national and global effects.

Table 3-1. Pollutants Resulting from Manufacturing

Greenhouse gas (GHG) emissions from direct and indirect energy use, land fill gases	**Global Climate Change**
Emission of toxins, carcinogens, etc. including use of heavy metals, acids, solvents, coal burning	Human organism damage
Water usage and discharges e.g., cooling and cleaning use in particular	Water availability and quality
Electricity and direct fossil fuel usage e.g., power and heating requirements, reducing agents	Depletion of fossil fuel resources
Land use, water usage, acid deposition, thermal Pollution	Loss of biodiversity
Emissions of CFCs, HCFCs, nitrous oxides e.g., cooling requirements, refrigerants, cleaning methods, use of fluorine compounds	Stratospheric ozone depletion
Land appropriated for mining, growing of bio—materials, manufacturing, waste disposal	Land use patterns
Material usage and waste	Depletion of non-fossil fuel resources
Sulfur and NOx emissions from smelting and fossil fuels, acid leaching and cleaning	Acid disposition

Source: STPI, 2009.

Principles of sustainable manufacturing are understood but much research is needed to commercialize the necessary technologies and incorporate sustainable manufacturing practices. Because environmental problems are often complex, solutions are complex as well. Trade-offs need to be made and more research, around a life-cycle view of manufacturing, often difficult for firms to take, is required to identify solutions.

If the manufacturing enterprise does not change (e.g., becomes less energy intensive, less polluting, and less resource-intensive), not only are there environmental costs, but competitiveness ones too.[x] For example, if markets abroad adopt sustainability standards that U.S. companies cannot abide by, it will hurt American exports. U.S. companies—with the support of the government—must evaluate and adjust their approaches toward the enterprise, processes, product design and product end-of-use to be able to stay competitive (or stay at all in these markets).

Leveling the Playing Field in Light of Increasing International Competition (the "Asymmetricity" Argument)

In a post WWII world, the United States did not have much manufacturing competition from other nations; Europe and Japan were still rebuilding their war-torn societies, and China and India were amongst the poorest nations in the world. Even with low (and possibly) inefficient investment in technology transfer, the United States was able to retain its technology edge. Even when key technologies went offshore (e.g., flat panel displays, advanced ceramics), the United States was seen as having comparative advantage because of its dominance in other aspects of the advanced technology sector.[xi]

But much has changed in the new millennium. In recent years, Governments in many countries are stepping in to invest in innovation and advanced technologies to supplement private sector investment (in accordance with the research as a public good model). Moreover, information and communication technologies have accelerated the pace at which information flows across national boundaries, and the U.S. does not retain its basic research edge for as long as it used to (so the inefficiencies of the past may not be as forgiving). With other nations much better organized to translate discoveries into innovation, and innovation into profits and jobs, America's comparative advantage is eroding. Offshoring of manufacturing activities may have accelerated this erosion. As Pisano and Shih argue: "decades of outsourcing manufacturing has left U.S. industry without the means to invent the next generation of high-tech products that are key to rebuilding its economy." According to advocates, the U.S. Government needs to make level or "tilt" the international playing field. While the asymmetricity argument in economic theory is made in the context of informational asymmetry,[xii] it applies just as much for competitiveness asymmetry, and requires adjustment.

Thoughts on the Appropriate Role of Government S&T Programs and Policies in Advanced Manufacturing

The previous sections summarize the argument that there is a role for the government in nurturing advanced manufacturing. What specifically is the role, especially for S&T programs? A review of the literature, and interviews with a small group of experts reveal three categories in which the government can play an appropriate role: (1) take an "ecosystem" view of the advanced manufacturing enterprise; (2) nurture the specialized workforce required by advanced manufacturing; and (3) study and benchmark the advanced manufacturing system, and disseminate good practices.

Ecosystem View of Advanced Manufacturing

Fund the gap between discovery and commercialization of advanced manufacturing. In the context of advanced manufacturing, where the linkages between discovery and commercial application and success are by definition more integrated, proponents believe that there is an especially more urgent need for continued support not just at the feeder end of the continuum[xiii] but also further down, into and beyond the "valley of death" (Hill 2007, Branscomb,[10] Tassey 2010). In fact, they argue, the government needs to fund the *ecosystem*[xiv] of the manufacturing enterprise (i.e., pushing not just S&T frontiers but also supporting process maturation, commercialization, and developing infrastructure and deploying platform technologies, see Figure 3-1). This is a move away from the model where only the "feeder" end of the "linear model[xv]" was funded.

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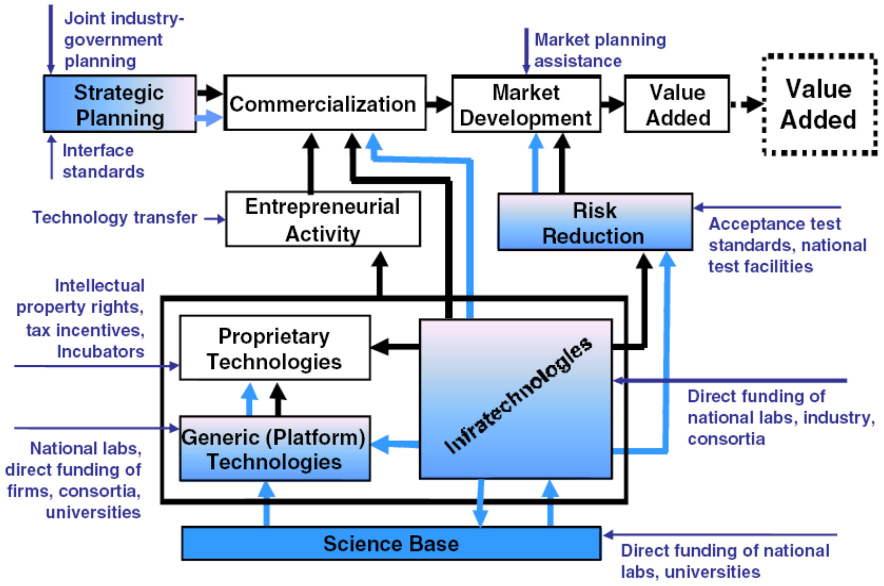
[10] Lewis Branscomb, "Research Alone Is Not Enough," Science 15 August 2008:Vol. 321. no. 5891, pp. 915–916 DOI: 10.1126/science.1160496



Source: Tassey, 2010.

Figure 3-1: Targets for Science, Technology, Innovation and Diffusion Policy

No doubt funding is needed at the feeder nodes (S&T) of the advanced manufacturing ecosystem.[xvi] For example, the National Science Foundation (NSF) funds the *Center for Layered Polymeric Systems,*[11] which is developing the technology to enable layering of two polymers using layer multiplication co-extrusion techniques. The thickness of these layers has reached nanometer sizes, allowing for unique optical, mechanical, transport, and structure properties in these layered polymer films, with applications in multiple sectors. Funding of research such as this needs to be maintained.

However, there is a crucial link between technology invention and industrial applications—from system development through sustainability. The U.S. has seen ideological struggle for supporting this link, with programs such as the Advanced Technology Program (ATP) being created but never receiving full-tilt long-term support (Hughes, 2005). There are disparate sources for this support—SBIR programs across multiple S&T agencies, being an important one. But currently, the civilian sector has no single entity that supports this link. There may be models in the U.S. Department of Defense *ManTech* program[xvii] or the German Fraunhofer Gesellschaft system (see question 5 below) and it may be appropriate for the government to examine them.

Procurement. Funding research and development is but one aspect of government support for advanced manufacturing. Some experts (e.g., Ruttan[12]) have shown that when government is a customer, and supports not just research and development but also procurement, innovation is incentivized. In the early day of the emerging semiconductor industry for example, government defense and aerospace agencies were the primary customers. Fairchild Semiconductor, the predecessor of Intel, received 80 percent of its revenues in the 1950s from direct government or government supplier contracts. The concept may be especially relevant for some types of advanced manufacturing. Vaccine development and production, for example, has accelerated ever since governments in the world have expressed interest in “advanced purchase commitments.”[xviii]

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[11] NSF Science and Technology Center (STC) program. http://clips.case.edu/clips.html, Last accessed March 7, 2010.

[12] Vernon Ruttan, *Is War Necessary for Economic Growth? Military Procurement and Technology Development,* 2006.

Fund development and deployment in industry. Some experts[13] believe that in a world where breakthroughs travel easily, their national origins are fundamentally unimportant, and the United States should not focus unduly on science and technology advancements. It is a controversial view, but according to these experts, it *doesn't* matter that Google's search algorithms were developed in California. As Bhide says, "A British researcher created the World Wide Web's protocols at Cern, a Switzerland-based European lab. A Swede and a Dane started Skype, the leading provider of peer-to-peer Internet telephony, in Estonia." Many of the high-level technologies associated with the iPod were developed outside the United States: compression software came from Germany, and the design of the chip came from the United Kingdom. The whole idea of an MP3 player came out of Singapore. But most of the value has been captured in the United States (Science and Engineering Indicators, 2010). Proponents of this view contend that the real economic payoff lies in innovations in how technologies are used, and in addition to funding research and development, the government should be supporting firms in two ways. Currently, support is stronger on the breakthrough front. For example, 1366 Technologies, an MIT start-up aiming to make silicon solar cells competitive with coal, secured both public (ARPA-E, $4 m) and private ($12.4 million from venture firms) to combine innovations in silicon cell architecture with manufacturing process improvements. One of the company's founders, MIT professor Ely Sachs noted the need for direct support for manufacturing. "The science is understood, the raw materials are abundant and the products work. All that is left to do is innovate in manufacturing and scale up volume production, and that's just what we intend to do."[xix] The company is building its pilot solar cell manufacturing facility in Massachusetts and plans to build industrial, 100 megawatt plants around the world.

Bhide proposes that support should be just as strong on the incremental front, and the government should just as much support firm-level tasks ranging from tweaking business models to trim costs, to fine-tuning company's business software in accounting departments.

Fund neglected and other emerging areas relevant to advanced manufacturing. Most current government funding in the manufacturing domain pushes the frontiers of science and technology. The research base of many other aspects of manufacturing, such as design, production process development, marketing, branding, etc. needs to be strengthened as well. In today's marketplace, supply chains are becoming supply networks; markets are becoming multidimensional, geographically and culturally. Competitive advantage is, more and more, coming down to talent and imagination in business organization and service, going beyond traditional emphasis on science- and engineering-based product innovations. There are many promising new ideas in the business world—open innovation and data mining for idea generation and sharing, IT for managing supply networks, and use of social media for marketing and branding, among others, and firms do not have the time horizons to pursue these developments. An appropriate role for the government is to fund research on these new challenges of and solutions to the marketplace.

Provide incentives for needed breakthroughs. Governments are uniquely positioned to mobilize and coordinate the efforts of the numerous organizations needed to confront "grand challenges" such as climate change. S&T programs and policies can incentivize innovative behavior in advanced manufacturing through use of inducement prizes or "grand challenge" type programs that capture the imagination of the public. There is evidence that when a funder defines the *outcomes* but not the *methodology*, revolutionary and unexpected advances can be made (Lockheed Martin's *skunkworks* program is often touted as an example). This type of funding can be expressed as a "prize"—which could be cash or prestige—as an inducement for innovation.[14] Typically prizes have been used for idea generation[xx] but they can be used to accelerate manufacturing as well. An example is the Progressive X Prize challenge in which a ten million dollar cash purse will be awarded to the teams that win a long-distance stage race for clean, production-capable vehicles that exceed 100 miles-per-gallon energy equivalent.[15] For a grand challenge,

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[13] Amar Bhide, *The Venturesome Economy: How Innovation Sustains Prosperity in a More Connected World*, 2008.

[14] Deborah D. Stine, *Federally Funded Innovation Inducement Prizes*, June 2009, available at http://www.fas.org/sgp/crs/misc/R40677.pdf, accessed February 27, 2010.

[15] Details at http://www.progressiveautoxprize.org/files/downloads/auto/PIAXP_Guidelines_V_1.3_12.21.09.pdf, accessed March 8, 2010.

a "systems" approach that involves funding of multiple activities from basic research to prototype development, in an integrated fashion is best. DOE's ARPA-E program is one such program that has the flexibility to sponsor R&D that spans multiple stages, from basic research to commercialization, and in areas that are otherwise too cross-cutting or multi-disciplinary to fit into the current S&T funding system.

Create regulations and standard setting in the area of advanced manufacturing is another appropriate role for S&T oriented agencies. Experts at NIST state that while hundreds of standards exist for ICs, almost none done for MEMs and other technologies relevant for advanced manufacturing. MEMS and evolving nanotechnology products tend to be specialized, custom products; and lack of standards can keep costs for new applications high, and hurt U.S. competitiveness both in domestic and international markets (NIST MEL).[16] Depending on how they are structured, regulations and standards may add to cost of production, but can also spur innovation. There are several examples in the environment domain where regulations triggered the discovery and introduction of cleaner technologies and environmental improvements.

Build the physical infrastructure. As Greg Tassey notes, "while products commercialized based on new technologies are private goods, the underlying technology platforms ("generic technologies") and supporting "infratechnologies" are derived from a combination of public and private assets."[17] This observation is important for two reasons. First, that infrastructure is the foundation that commercialized technologies are built upon and enables their design, development, and production, and, second, that the government can and should play a role in fostering early investment *in under-supported* manufacturing infrastructure R&D, supply chain integration, manufacturing systems integration, and technology maturity lifecycle management. Emerging firms that lack design support, tools, mature processes, and technical and business know-how must demonstrate some plan or ability to develop these in order to attract the requisite investment capital to get off the ground. Existing firms must constantly refine and renew the technology platform and manufacturing processes that they employ in order to keep up with competitors, let alone capture competitive advantage. Therefore, manufacturing infrastructure innovation is seen as essential to both new and existing firms and would benefit from a government commitment to providing access to world-best R&D, processes, and technologies.

Skill-Building for Advanced Manufacturing

A key factor in responding quickly to customer needs and developing new processes and products more rapidly (two important attributes of advanced manufacturing) is a workforce that is ready for these challenges. Several experts, especially from the manufacturing industry, lamented the lack of appropriately trained workers from U.S. institutions. This dearth (among other reasons to be sure) leads them to manufacture elsewhere, especially Asia. When asked if his company was being held back by weak science and math education in America's K-12 schools, Paul Otellini, the CEO of Intel commented, "As a citizen, I hate it. As a global employer, I have the luxury of hiring the best engineers anywhere on earth. If I can't get them out of MIT, I'll get them out of Tsinghua."

Experts with whom we spoke indicated that to aid the United States in growing its advanced manufacturing economy and to overcome technological challenges, workers need to be better and more differently educated. For example, in a recent report, James Duderstadt of the University of Michigan proposed that undergraduate engineering should be reconfigured as an academic discipline, similar to other liberal arts disciplines in the sciences, arts, and humanities, allowing students to benefit from the broader educational opportunities for a lifetime of further learning rather than professional practice. Simultaneously, engineering (or, perhaps more broadly, technology) should be included in the liberal arts canon undergirding a twenty-first–century undergraduate education for all students.[18] The government may need to consider a range of new ideas such as this to revamp education for manufacturing related jobs.

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[16] NIST MEL homepage http://www.nist.gov/mel/, accessed January 29, 2010.

[17] Greg Tassey, "Rationales and mechanisms for revitalizing US manufacturing R&D strategies," op. cit.

[18] James Duderstadt, "Engineering for a Changing World: A Roadmap to the Future of Engineering Practice, Research and Education," The Millennium Project, University of Michigan, 2008.

Some experts also propose de-emphasizing the apex of the education system (i.e., production of advanced degrees in S&T) and investing scarce government resources further down in upgrading community college programs. In his book, the *Venturesome Economy*, Bhide says, “In the end, it comes down to individuals, and you don’t need to be a trained scientist or engineer for this broad swath of creatively productive work.... You need a somewhat more open mind, a willingness to experiment and to innovate in the use of technology, not create it.” Community colleges also have a role in retraining workers (and out-of-work workers) in the emerging tools and technologies of the ever-advancing frontiers of advanced manufacturing. Other experts have recommended apprenticeship programs, such as those in Germany that produce deeply knowledgeable workers, and point to international experiences (e.g., internships at firms abroad) to prepare U.S. workers for the global work- and marketplace.

Investing in skill-building (and not simply increasing numbers of scientists and engineers) would enable both students and workers to be better prepared for advanced manufacturing jobs and provide one less reason for firms to justify offshoring.

Understanding the Rapidly Evolving Manufacturing Enterprise

Understand the role of manufacturing. Another important role for the Government is to improve understanding of the role of manufacturing in wealth and employment creation (sometimes at cross purposes) and the interrelationship and interdependence of manufacturing with other sectors. Manufacturing is, for example, seen as part of a portfolio of emerging sectors (together with green businesses, biotechnology, and other emerging industries) that will create the jobs of the future. While advanced manufacturing is part of the solution, the industry may be too small to create the millions of jobs that are needed right away. The semiconductor and biotech industries, for instance, each employ less than one-half of one percent of U.S. workers; clean-technology workers, such as those who design and make wind turbines and solar panels, account for 0.6 percent of the workforce (McKinsey Global Institute). Some experts believe that we will be able to generate significant numbers of new jobs only by spurring broad-based job growth across the economy, particularly in big sectors such as retail, wholesale, business services and health care.[19] High-technology innovations will help employment grow over the long term, as new technology spreads throughout the economy and transforms other, larger sectors.[xxi] A better understanding of the larger ecosystem will not only help define the “scope” of manufacturing and the range of leverage points the Government has, but also scale expectations regarding the speed with which new jobs arrive.

Understand the role of incentives and policies. There are other areas of research. For example, as some posit, if the location of breakthrough research is not important, would funding or tax break for research be less important? How accurate is the hypothesis that the key to boosting employment quickly is to help small businesses? According to some sources (MGI, 2010), new jobs come from both small and big businesses, and the pace of job creation depends on more than the size of the business, and timing is important. For example, the MGI reports that during the recent expansion of 2002-2007, most of the net new jobs came from local service sectors, such as health care, construction and real estate—which comprise both large and small businesses.

Examine best practices. It is also important to analyze successes and failures of government investments and lessons that can be drawn from them. Massachusetts, for example, has all the ingredients of an innovative economy—world class educational institutes, well educated labor force, a thriving venture industry and Federal dollars. Despite all these advantages, the state has high unemployment. What lessons can be drawn from this system? There are other important questions as well. For example, how can “grand challenge” experiences in other sectors (energy, space travel, etc.) be replicated in the manufacturing sector? How can a developed country like Germany retain its high-technology manufacturing edge much better than the U.S. has been able to? What can be learned from strategies used in certain emerging markets (for example, China has large industrial zones devoted to specific industries that offer tax breaks, cheap or free land, workforce training, plenty of water and power, and agencies that serve as one-stop shops for all of the necessary permits and regulatory approvals)?

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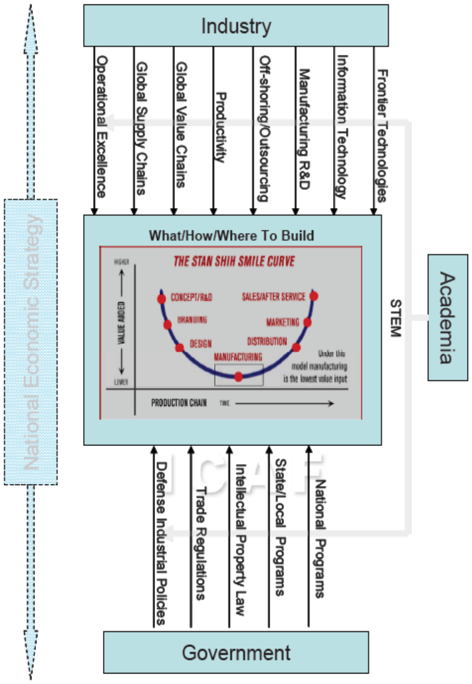
[19] McKinsey Global Institute (MGI) in “Five Myths About How to Create Jobs,” *Washington Post,* February 7, 2010, available at http://www.mckinsey.com/mgi/mginews/five_myths.asp, accessed February 22, 2010.

Disseminate best practices. An appropriate role for the government is to lower informational asymmetries through better dissemination of relevant information. Best practices (as well as breakthrough research findings) need to be disseminated to enterprises. Through programs such as the Manufacturing Extension Partnership (MEP) and others, S&T agencies can bridge this gap. Indeed, one of the most appropriate roles the government can play is to be a "connector" in the manufacturing ecosystem—and make the learning curve less steep for all stakeholders.

Other Observations on the Role of Government

It is important to note that the role of the government in nurturing advanced manufacturing is not restricted to just S&T. There are other criteria that determine success. Not the least of which are regulations, intellectual property regimes, and taxes.[xxii] Industry representatives frequently point to the U.S. having the second highest level of corporate taxes in the world. In a recent interview Paul Otellini, the CEO of Intel, pointed out that "a new semiconductor factory at world scale built from scratch is about $4.5 billion—in the United States. If I build that factory in almost any other country in the world, where they have significant incentive programs, I could save $1 billion." An example—as a result of all the tax breaks the Chinese government threw in, the last factory Intel built from scratch was in China. A discussion about taxes may be sensitive and not in the domain of S&T, but it is an important one.



Source: Manufacturing Industry Study Group, National Defense University, 2009

Figure 3-2: Elements of Advanced Manufacturing

In other words, there are many elements that need to be aligned to create a successful advanced manufacturing enterprise in the United States, and S&T agencies are only one part of the overall equation. Figure 3-2 is one vision of the integrated planning effort that some experts believe needs to be made to resuscitate manufacturing in America.

Appropriate Line between Government and Private Sector

There is little hard data or arguments in the literature regarding when the government should "exit" and industry "enter." In most cases, there simply may not be hard exit strategy. Many of the biggest advances of our time began in industry and were iteratively developed in academia and industry (with both receiving government funding), and vice versa. As the famous "tire track"[20] chart published by the National Academies suggests, research in areas such as client-server computing, local area networking, RISC processors, RAID/disk servers, among others, originated in firms such as IBM, DEC, Xerox Parc and Bell Labs, and evolved in universities like Berkeley, Stanford and MIT, and then grew back in industry. Although basic research performed at universities is the foundation of much industry success—after all, Google began as a research project by two Ph.D. students at Stanford University—the NAS tire tracks chart underscores the interdependence of industry and government funding.

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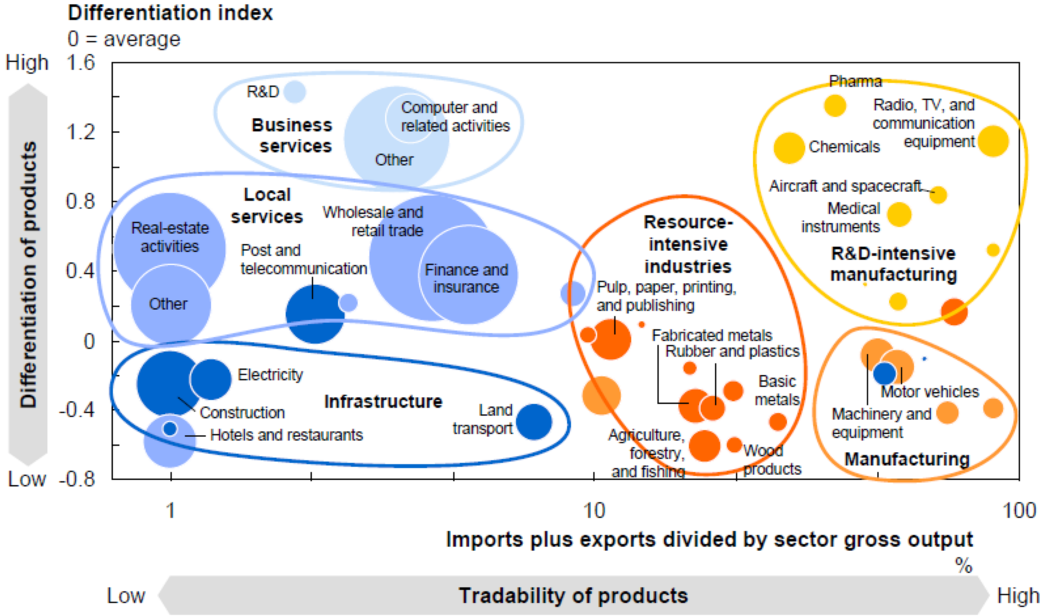
[20] The National Academies Computer Science and Telecommunications Board, *Innovation in Information Technology*, 2003, available at http://www7.nationalacademies.org/cstb/pub_itinnovation.html, accessed 17 July 2007.

Often government support is combined with private funds to develop technologies. For example, 1366 Technologies referenced above, secured both public (ARPA-E, $4 million) and private ($12.4 million from venture firms) to combine innovations in silicon cell architecture with manufacturing process improvements.

Another example of this iterative funding is Donald Sadoway, a professor in the material science and engineering department at MIT who is developing liquid metal grid-scale batteries. The research was initially funded by the government, and then by MIT’s Deshpande Center and the Chesonis Family Foundation, which allowed the concept to be developed to the point of demonstrating a proof-of-principle at the laboratory scale. At this point larger scale funding was needed to develop the technology further. The U.S. Department of Energy (DOE) stepped in for the scale-up. Believing that the technology “could revolutionize the way electricity is used and produced on the grid, enabling round-the-clock power from America’s wind and solar power resources,” the project recently received $7 m from DOE’s ARPA-E program, with the intent that it would ultimately use low cost, domestically available liquid metals to store energy at grid-scale. Without both private and government support, the technology is not likely reach manufacturing scale application.

Sectoral Differences

The nature of the sector matters for the kinds of policies that are effective in promoting competitiveness. How much it matters is a matter of opinion. For example, a recent report from the McKinsey Global Institute (MGI 2010) contends that in traded sectors, where success requires local companies to be competitive in the global marketplace, it is harder for Government policy to impact performance as directly. The report presents a framework that lays out the relative role of different policies based on the degree of “differentiation” and “tradeability (see Report and Figure 3-3).

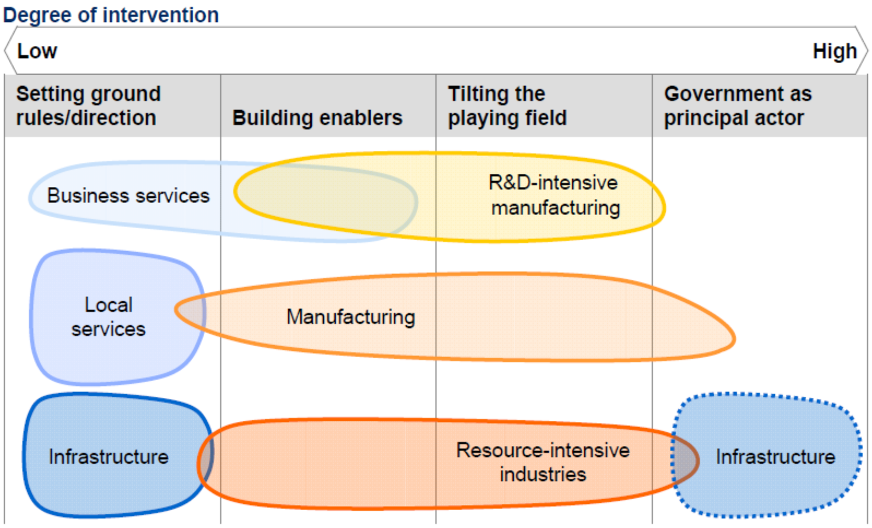


Source: MGI, 2010.

Figure 3-3: Sectoral Groups by Differentiation and Tradeability

Based on differences between sectors, MGI has developed a spectrum of public policy interventions ranging from a hands-off approach limited to creating the necessary market institutions, to being a central operator (Figure 3-4).

According to MGI, even within the R&D intensive manufacturing sectors (that would include advanced manufacturing as defined in this document), the maturity of the industry affects the way government can support the growth of innovation. Unlike the mature capital-intensive semiconductor industry, in emerging high-technology segments (like clean technology) the government should refrain from defining the technology or solution of choice, and focus instead on playing an enabling and possibly coordinating role, creating demand for early innovative activities, and ensuring that the regulatory environment provides the right incentives for firms; ensuring sufficient flow of research findings, and addressing any stands or coordination issues.



Source: MGI, 2010.

Figure 3-4: Policy Tools as Applicable to Sector Competitiveness Drivers

Other experts believe that in general, the potential intervention points are determined by the public good content of either a technology element or an activity, and they are generally the same across technologies and economic sectors. However, the ranking in terms of severity of underinvestment can vary across technologies, and rankings certainly change over a technology's life cycle (for example, process technology takes on increasing importance as a technology gains market share and matures so therefore do market failures associated with processing).[21]

Some experts believe that there is no reason to expect that government action will vary by industry or sector unless there are *a priori* reasons to think that the barriers in one industry or sector are "greater" than in another industry or sector. Theoretically speaking, one could hypothesize that in industries or sectors where technology life cycles are short and rapidly changing (e.g., biosciences and related experimental equipment), there is likely a greater underinvestment by firms, and there is likely more tacit knowledge that is needed rather than codified knowledge. Building on Albert Link's forthcoming book, one could envision a "checklist" to examine how the intervention point between various sectors varies:[22]

- Is the technical risk associated with the underlying R&D higher for the sector over others?
- Are capital costs to undertake the underlying R&D with high market risk higher?
- Does it take longer to complete the R&D and commercialize the resulting technology?
- Is there a greater likelihood that the underlying R&D spills over to multiple markets and is not especially appropriable within the sector?
- Does market success of the technology in the sector depend on technologies in different industries?
- Is the probability that property rights cannot be assigned to the underlying R&D higher?
- Is there a greater likelihood that the resulting technology that must be compatible and interoperable with other technologies?
- Do stakeholders in the sector show a high risk of opportunistic behavior when sharing information about the technology?
- Does the sector operate on higher levels of tacit (vs. codified) knowledge?

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[21] Greg Tassey, email correspondence, March 05, 2010.

[22] Based on Albert Link and John T. Scott, Public Goods, Public *Gains: Calculating the Social Benefits of Public R&D* (Oxford University Press, forthcoming).

Conclusion

As Pisano and Shih point out, the Federal Government has long played a central role in supporting technological innovation, and it similarly has one in the area of advanced manufacturing. Recognizing the interplay between manufacturing and other sectors, the best strategy is sector-dependent, flexible and portfolio-based, and would involve the use of a variety of mechanisms to support different parts of broadly-defined manufacturing innovation ecosystem. One role worth emphasizing is that of a "connector"; developing and expanding pathways for collaboration between academia, industry, and government that would create synergies across organizations to support each tier of the manufacturing environment. Ultimately, the most appropriate role for the government in advanced manufacturing is in fact to create the "climate"—the political rhetoric and systems needed to create momentum. This momentum, experts claim, is far more important than funding piecemeal efforts. The current spotlight on energy is a good example of the "climate" that needs to be in place to promote an important idea.

Endnotes for Question 3

i By traditional comparisons, the United States remains the world's largest manufacturer. China, the nearest competitor, has a much larger population, and per-capita manufacturing output is correspondingly much lower. Job losses in the U.S. manufacturing sector may be attributed to foreign competitors, shifts in domestic demand for manufactured goods, or increasing labor productivity; a similar set of possibilities could be given for trade imbalances.

ii According to the Bureau of Economic Analysis, every $1 of final demand spent for a manufactured good generates $0.55 of gross domestic product (GDP) in the manufacturing sector and $0.45 of GDP in nonmanufacturing sectors.1 http://www.trade.gov/media/publications/pdf/manuam0104final.pdf, accessed March 3, 2010.

iii The United States bases its national security on technological superiority, not matching adversaries in numbers. The ability to make the advanced weapons (whether land, air or sea) employing such technologies as advanced hyper spectral sensors for intelligence, surveillance and reconnaissance; carbon-fiber nanocomposites for protection and light weight, high efficiency propulsion for endurance and speed, are crucial to achieving our security advantage. The importance of making the products of advanced technologies for our future security has been emphasized recently by a study of the National Defense University (NDU, 2009); the Defense Advanced Research Projects Agency (DARPA, 2010); and the Secretary of Defense in the Quadrenniel Defense Review (Secretary of Defense, 2010).

iv Even high-technology firms, such as integrated circuit (IC) producers, began to move their most advanced fabrication facilities offshore in the 1990s, having already moved packaging and testing offshore earlier (although leading U.S. IC firms generally located their first-of-breed advanced fabrications in the United States near their product design centers, this may no longer hold in the future (Van Atta, 2010).

v Data from BLS show that in 2008, manufacturing wages for non supervisory positions (positions that typically do not require higher education) were about a fifth less than wages in the construction and mining sectors, and about the same or less for similar workers in the private service sector (Source: Bureau of Labor Statistics, ref:http://data.bls.gov:8080/PDQ/outside.jsp?survey=ce). This closing gap provides an additional incentive to shift to the type of manufacturing that requires higher skills and therefore higher wages.

vi When a market left to itself does not allocate resources efficiently, market failure occurs. Market failure is typically attributed to market power, imperfect information, externalities, and public goods. The explicit application of market failure to justify government's role in innovation—in R&D activity in particular—is a relatively recent phenomenon within public policy.

vii The market does not price knowledge in discrete bundles and thus because of such indivisibilities market prices may not send appropriate signals for economic units to make marginal decisions correctly. (Link and Scott, 2010)

viii The fundamental rationale for government support of R&D rests on the idea that the social rate of return on R&D investment is greater than the private rate of return. That is, the overall benefit to society, when all benefits are considered, exceeds the private benefit that accrues to the individual firm that performs the R&D. From the policy perspective, the private sector or individual firm does not have as much incentive to carry out R&D as is socially optimal because it cannot capture all of the benefits of its R&D investment (Mansfield 1996; Griliches 1993; Stiglitz 2005). The overall benefit of R&D exceeds the private individual return because much of the utility of R&D accrues to those other than the company carrying out the R&D. These positive externalities also "spill over" to other firms and individuals not directly involved in the original R&D work through patents, publications, and other means of industry knowledge dissemination.

ix Negative externalities occur when firms do not take into account the impact of an economic activity on outsiders. For example, the market may ignore the costs imposed on outsiders by a firm polluting the environment.

x Europe and Japan are implementing standards and policies to achieve SM, e.g., closed-loop material flows, promote product stewardship and eliminate hazardous substances. For example, the EU Plans to spend $800-$900 million in Sustainable Manufacturing R&D (Interview with Rahimifard). In Japan, the Council for Science and Technology Policy (CSTP), with the Office of the PM, emphasized manufacturing technologies as a strategic promotion area. METI promotes switching from a manufacturing oriented "single engine" to a "twin engine" of manufacturing and services industries, rather than shifting its axis (like the US) from manufacturing to service industries. WHAT IS AIST??AIST formulated the medium term plan based on the concept of "minimal manufacturing." China too has begun efforts in the area; a White Paper China's Population Environment and Development in the 21st Century specifies the objectives, principles, priority areas, and safeguard measures for the country's sustainable development in the early 21st century. Source: F. Jovane et al. / CIRP Annals—Manufacturing Technology 57 (2008) 641–659. Sources: Conversations with EU experts and review of documents at ftp://ftp.cordis.europa.eu/pub/ims/docs/1-3-rode.pdf

xi The Census Bureau has developed a classification system for internationally traded products that embody new or leading-edge technologies.

xii Information asymmetry occurs where one side of a transaction (buyer/seller or externality generator/affected party) has more/less information about a good's attributes than the other side.

xiii The theoretical rationale for Public Support of Early Stage Technology Development (above and beyond 'general support' as discussed in Footnote 1 above, is that there exists a funding gap for entrepreneurs who seek to transition from scientific invention to commercial innovation. Some argue that only minimal intervention by the government is needed to ensure economic efficiency.

xiv The dynamic system of interconnected institutions and persons that are necessary to propel technological and economic development has been described the U.S. innovation ecosystem. This ecosystem includes a range of actors from academia, industry, foundations, scientific and economic organizations, and government at all levels. While widely recognized as non-linear and iterative, in its most simplified form the innovation process can be viewed as generating both new knowledge (education and training) and technology (development and commercialization) that is moved from basic discovery research to the marketplace. In this model, the results of basic science, primarily funded by the Federal government and private foundations, are translated into applied science or basic technology, where research is in turn funded by a variety of public and private entities, with venture capital often providing additional funding as the science and/or technology mature. If the research results are successful and appropriate for the marketplace, they are then turned into commercial (or publically beneficial) processes and products that drive the economy. A host of conditions influence this ecosystem, such as legal and regulatory considerations. The organization of the innovation ecosystem is not rigidly planned with well-defined roles for the various actors. As a result, the relative positions of each actor, as well as the conditions encouraging or restraining the innovation process, can change continually. (From PCAST report: University-Private Sector Research Partnerships in the Innovation Ecosystem, available at http://www.whitehouse.gov/files/documents/ostp/PCAST/past_research_partnership_report_BOOK.pdf, Accessed February 15, 2010)

xv The basic linear model of innovation posits a process that moves from one stage to another: Basic Research --> Applied Research --> Development --> Diffusion/production. There are countless variations, which differing descriptions and titles for the stages. There are also variations that employ feedback mechanisms. But they are essential the same: science goes in and products (innovations) come out.

xvi It may be important to point out that the government supports a very small fraction (under 9 percent of the total R&D spending on manufacturing in 2008) of the R&D devoted to manufacturing. Manufacturing was responsible for about 70% of all U.S. research and development spending in 2007, with total research and development spending of $187 billion in that year alone. The US investment is lower than many other countries including Germany, Japan and South Korea (90% each), France (96%), Finland (84%), and Belgium (77%). (SEI 2010)

xvii See https://www.dodmantech.com/pubs/ManTech_Exec_Sum.pdf, accessed March 5, 2010.

xviii Under this mechanism, credible sponsors commit, in advance of a vaccine's development and licensure, to a minimum price that would be paid per person immunized for an eligible product; such a commitment greatly reduce the uncertainties that are specific to products for low-income country markets and thereby put malaria on a more equal footing with health conditions that affect affluent populations in firms' R&D allocation decisions.

xix From http://findarticles.com/p/articles/mi_m0EIN/is_2008_March_27/ai_n24959687/, accessed February 26, 2010.

xx An example is the DARPA Grand Challenge, a prize competition for driverless vehicles, funded by the Defense Advanced Research Projects Agency (DARPA) to further its mission to sponsor revolutionary, high-payoff research that bridges the gap between fundamental discoveries and their use for national security. Through high profile competitions, DARPA nurtured the development of technologies needed to create fully autonomous ground vehicles capable of completing a substantial off-road course (and later autonomous operation in a mock urban environment) within a limited time. DARPA has continued the prize model. A recent high profile "prize" activity was the DARPA red balloon challenge, where a team had to be the first to submit the locations of 10 moored, red, weather balloons at 10 fixed locations in the continental United States.

xxi The McKinsey report points out that while the semiconductor industry alone doesn't account for much U.S. employment, the computer revolution has fueled the growth of other industries such as retail and finance; similarly, the clean-technology business by itself doesn't employ many people, but its developments could transform a big sector such as energy, creating new business models and new jobs.

xxii Proponents also point to the need to encourage firms to engage in more R&D by providing them with larger R&D tax credits or making the existing credits, currently temporary and periodically renewed by Congress, permanent (ITIF, 2007). They contend—based on historical data—that this change would decrease uncertainly associated with long term R&D. There are skeptics of this view however who argue that the credit simply rewards firms for R&D that they do anyway. For other critics, the argument is that R&D tax credits don't influence the geographic location of where firms conduct research: they argue that tax incentives in particular, and cost differentials more generally, have little influence over where companies conduct R&D. Rather, they assert that companies are attracted by R&D talent pools (which is why, they say, US firms will go abroad and set up R&D operations even if the US offers permanent tax credits for US-based R&D facilities). Other experts argue that that it is better to increase funding for federal research (instead of subsidizing industry). If R&D is indeed a public good, they say, firms will invest in research with the highest private payoff (e.g., development), which may not have the highest social payoff (e.g., basic research).

Question 4: What are historical examples where Federal or state science and technology programs, policies, or activities have enhanced advanced manufacturing?

Government Mechanisms for Supporting Advanced Manufacturing Technologies

Federal and state government support for enhancing advanced manufacturing has ranged from Federal Agency support of mission-related projects to innovative partnerships with academia and the private sector. This paper discusses three roles government has played in support of advanced manufacturing technologies:

- Early investor, in which the government identifies promising industries to fund in later stages of the innovation process;
- Leading customer, in which the government provides guaranteed first purchases for a product; and
- Partner in Public Private Partnerships, in which the government jointly funds and operates projects that would not otherwise be initiated within any one sector alone.

Government support through these roles provides capacities that would not be met in other ways. The remainder of this paper discusses these roles in detail.

Federal Government as an Early Investor

The Federal Government has served as a fundamental investor in a number of new manufacturing technologies. While S&T funding has historically invested heavily in basic research—scientific inquiry aimed at discovery and expanding fundamental knowledge—the Government has also provided a crucial role in supporting technologies at later stages of development and deployment. These investments have mainly been focused on mission agency needs, especially national security imperatives.

The Department of Defense (DOD) has developed manufacturing technologies and has fostered their implementation in a range of applications, such as aerospace propulsion, aircraft structures and materials, sensors and sensor systems, and microelectronics. NASA and DOE have also served as early investors in manufacturing technologies. The examples below provide a snapshot of the wide impact agency funding has had on moving advanced manufacturing technologies forward:

- DOD investments in new materials and materials production processes contributed greatly to the development and use of matrix composite materials, including the recent developments of nanocarbon polymer matrix composites.
- DOD R&D and initial procurement contracts fostered the development and production of the first integrated circuits.
- DOD has made sustained investments in a broad range of microelectronics production, including fundamental investments in the production processes for millimeter microwave integrated circuits (gallium arsenide MIMICs) and microelectromechanical systems (MEMS).
- DOD and NASA have made major investments in turbine engine and rocket engine propulsion production.
- NASA has had a substantial impact on materials, propulsion, and electronics technology production.
- DOE has made fundamental contributions to a broad array of materials and electronics manufacturing. For example, the Extreme Ultraviolet Lithography for nanoscale integrated circuit production—now in development—grew out of joint Lawrence Livermore and Sandia Laboratories applied research.

Moreover, Federal applied research investments have generated substantial spillover into the broader economy and have fostered and ignited commercial production in these application areas. Mission-agency applied R&D has been crucial to the development of U.S. advanced manufacturing and has contributed to the success of dominant commercial companies, such as Boeing, Texas Instruments, and Pratt & Whitney. DOD investments are now spurring the development of new, high-risk products and processes, such as nanoelectronics, nanomaterials, and biomanufacturing of vaccines using genetic engineering.

Federal Government as a Leading Customer

The Federal Government has also driven manufacturing of new technologies by serving as a leading early customer of technologies that they supported. The role of the Federal Government as an early stage customer has been vital to the ability of firms developing advanced technologies to be able to support the transition to manufacturing. Federal support of a technology also serves as a leading indicator of its value and prospects to internal corporate management and to the investment community, thereby encouraging these groups' further investment in manufacturing.

This was the case for jet propulsion and composite materials for aircraft as well as for other technologies driven by military imperatives.

Government as lead procurer has also applied to broader, less military direct technology areas. An example is DARPA's development of the "internetted" computer workstation, which led to Sun Microsystems and Silicon Graphics. Defense Advanced Research Projects Agency (DARPA) encouraged and financially supported other projects under its Information Processing Technologies program to acquire the new workstation systems for the design and development of new types of computer chips and other advanced computer technologies.

Beyond the direct funding of mission-related production processes, the Federal government has increasingly supported joint-funded public-private partnerships that are cooperative investments with private enterpris**e**. These are discussed in the section that follows.

Federal Public-Private Partnerships

Overview

Federal public-private partnerships (PPPs) are jointly funded and operated through a partnership among government, one or more private-sector companies, and often academic and non-profit entities (Federal laboratories and other research organizations). Due to the decline in many areas of U.S. manufacturing and challenges resulting from an increasingly globalized economy, PPPs have been advanced as one possible approach to spur a revitalization of the manufacturing sector. The common characteristics include:

- PPPs provide a mechanism to encourage joint action in areas with high-entry barriers and uncertain profitability.
- PPPs leverage the diverse skills and exploit the potential for research synergies, complementarities, scale economies, and knowledge-sharing among participants.
- PPPs allow higher-risk[1] and larger-scale projects to be undertaken that are more ambitious and technically challenging than typical company and industry projects. [2] [3]
- PPPs accelerate the development and deployment of new technologies that have the potential for radical change in one or more industrial sectors and that lead to large economic and societal benefits.

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[1] High risk is defined in several ways, alone or in combination: (1) technical risk, in which novel ideas are undertaken but the chance of success is low; (2) acceleration of technology development, where technical risk is high, in part, because of the short window of time to develop and commercialize a new technology; (3) R&D that falls outside the direct interest of individual firms because it provides a collective "club" good. These are akin to public goods in that the individual firm will not fully appropriate the benefits from the technology and thus will under-invest or make investments that are only very narrow and thus "below critical mass." That is, they are industry sector–level issues that the individual firm cannot justify taking on alone. Hence there is a need for a Federal role to lower the risk and an industry role to share the risks and benefits.

[2] Bronwyn H. Hall, Albert N. Link, and John T. Scott, *Universities as Research Partners*, NIST GCR 02-829, Gaithersburg, MD, 2002.

[3] Dyer, Jeffrey H., Benjamin C. Powell, Mariko Sakakibara, and Andrew J. Wang, *Determinants of Success in R&D Alliances*, NISTIR 7323, 2006, available at http://www.atp.nist.gov/eao/ir-7323/contents.htm [last accessed February 28, 2010].

Assessments have identified that successful PPPs resolve four fundamental issues: [4]

- the financial and in-kind contributions that each party brings to the table,
- the equity share of each partner in the gains and losses that result from the project
- the governance mechanisms that guide the operation of the PPP, and
- the frequency of inter-party communication.

In a PPP the various parties involved in the consortium assume substantial financial, technical, and operational risk in the project, distributing the burden based upon a model agreed upon in advance. Each partner brings a variety of resources and competencies to the partnership. For example:

- **Government** may provide funding, facilities, oversight, and/or guaranteed first purchases.
- **Industry** may provide funding, knowledge, technical know-how, intellectual property, personnel, management, and/or implementation capabilities.
- **Universities** may provide knowledge, intellectual property,[5] academic labor (PIs and students), and/or facilities.

To stimulate technical innovation, PPPs produce the following benefits:[6]

- **Generating scientific and technical knowledge** that is shared among many partners that leads to greater know-how, expertise, and new capabilities that further innovative activity. Output includes publications, patents, licenses, analytical models, algorithms, new research equipment, reference samples, and prototype products and processes.
- **Creating and disseminating intellectual capital** through licensing agreements with U.S. companies and investors.
- **Building research and professional networks** among the partners.
- **Moving technologies to market**. PPPs can facilitate technology transfer from invention to innovation.

Few programs measure success consistently across their programs. That being said, the general rule of thumb is that 10 percent of the projects are unprecedentedly successful, and the benefits from this top 10 percent far exceed the cost of the entire program. These are often game-changing and radical innovations that allow for leapfrogging technologies and practices to emerge. This is consistent with what venture capitalists find. However, even those projects that are not as successful as the top 10 percent generally create and disseminate knowledge and may result in commercialized products and processes. Finally, even the projects that are at the bottom 10 to 20 percent, the “failures,” are still useful in that one often learns as much, if not more, from these failures.[7]

There have been several PPPs in the United States, but there have been many in other countries. For example, SEMATECH was based on initial Japanese VLSI consortia, but then kindled both SELETE in Japan and several PPPs in Europe, including IMEC based in Belgium.[8] Notable historical examples of U.S. PPPs that have produced a portfolio of successes, SEMATECH and the ATP, are discussed in detail below; short descriptions of other PPPs are also provided.

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[4] Ibid.

[5] In the Advanced Technology Program, three out of five applicants propose projects that are based on university research. See *ATP Survey of Applicants, 2002*, NIST GCR05-876, June 2005, Fact sheet R-5: *ATP Helps Companies Work with Universities*. http://www.atp.nist.gov/eao/2002survey/r5-atphelps.htm [last accessed February 28, 2010].

[6] *An Assessment of the SBIR Program at the National Science Foundation*, National Research Council, 2008.

[7] *Measuring ATP Impact*, GCR 06-899, March 2007, available at http://www.atp.nist.gov/eao/gcr06-899.pdf [last accessed February 21, 2010].

[8] See *University-Private Sector Research Partnerships in the Innovation Ecosystem*. Appendix A, PCAST. 2008, http://www.whitehouse.gov/.files/documents/ostp/PCAST/past_research_partnership_report_BOOK.pdf [last accessed February 21, 2010].

Historical Examples of Public-Private Partnership Support for Advanced Manufacturing: SEMATECH and the Advanced Technology Program

SEMATECH[9]

SEMATECH was established by Congress in 1987 under the authority of the Defense Appropriations Act, which allowed for the creation of a consortium of industry firms under Government support. It was created as a means for U.S. IC companies to re-establish their competitive leadership in IC manufacturing processes, which had been lost to the focused collaborative efforts of the Japanese IC industry through the oversight and support of the Japanese government's Ministry for International Trade and Industry (MITI). The Japanese had, in a few short years, captured a major share of the integrated circuit memory market and appeared poised to gain a majority of the IC market.

SEMATECH was established as a public-private partnership with a 50/50 split between DOD and chipmakers to fund its annual budget of $200 million. Its enabling legislation left SEMATECH's daily management to the participating firms, with DOD serving a limited oversight role as a non-voting member of the board.

SEMATECH became a test integration facility for tool and equipment suppliers, providing for direct contact with their U.S. customers to be evaluated under a common set of production requirements. In addition, SEMATECH allowed individual company researchers to work on prototype production processes along with the SEMATECH staff, promoting knowledge transfer. Through these interactions, researchers were better able to understand production issues, which permitted them to implement complex IC manufacturing processes at their home companies and accelerate cycle times (Moore's Law). SEMATECH enabled suppliers to interact with the leading IC process development firms, IC firm researchers were able to communicate their needs and problems directly to a set of major suppliers, and chipmaker researchers had the unprecedented ability to talk with each other about daunting production processes.[10]

During its initial years, SEMATECH's organizational focus shifted as it experimented with the best way to accommodate the interests of its competing members and the supplier industry. In 1992, SEMATECH carried out an internal reorganization and explicitly defined a new long-range strategy (SEMATECH II) focusing on accelerated, 2-year rhythm for technology introductions. This strategy entailed the institutionalization and acceptance within the U.S. semiconductor industry of a roadmap process, which represented a systematic attempt by all major players in both the U.S. integrated circuit industry and its materials and equipment suppliers to jointly do the following:

- Address the complex array of likely new technologies required for manufacturing next-generation chips,
- Coordinate the required timing for their introduction, and
- Intensify R&D efforts on the pieces of technology that were likely to be "showstoppers" and require further work if the overall schedule was to succeed.

The consortium decided in 1995 to join with foreign producers in an international partnership to quicken deployment of materials and equipment designed for use with 300mm (12-inch) silicon wafers (I300I). In 1996, SEMATECH requested that U.S. Government funding be terminated. A new International SEMATECH was formed in 1998 to house the increasing number of projects involving foreign chip producers. Finally, in 1999, the original SEMATECH reorganized itself as International SEMATECH.

SEMATECH was viewed as a major success in Japan. The SEMATECH model (ironically, a U.S. reaction to the Japanese VLSI consortia of the 1970s) became the inspiration for a new generation of Japanese semiconductor R&D consortia in the mid-1990s. Japan's semiconductor industry formed its own R&D consortium, SELETE, with a

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[9] Based on Kenneth Flamm, "Economic Impacts of International R&D Coordination: SEMATECH and the International Technology Roadmap," *21st Century Innovation Systems for Japan and the United States: Lessons from a Decade of Change: Report of a Symposium, National Academies of Science and Engineering*, 2009, and Richard Van Atta, et al, *Semiconductor Dependency*, Institute for Defense Analyses, 1988.

[10] SEMATECH provided limited funding to the tools and equipment makers themselves.

single non-Japanese member (South Korean producer Samsung). At the start of this century, two transnational R&D organizations coexisted within the international semiconductor industry—SELETE, with headquarters in Japan, and International SEMATECH, with headquarters in the United States. After 1997 SEMATECH's "national" technology roadmap was replaced by "International Technology Roadmaps" sponsored and coordinated through these two global R&D consortia and semiconductor industry associations in the United States, Europe, Japan, Korea, and Taiwan.

SEMATECH is frequently cited as a model public-private partnership for having provided U.S. integrated circuit firms with a mechanism to stabilize the U.S. industry's competitive position. However, SEMATECH had several distinctive elements:

- The firms that formed it were the dominant firms in the industry at the time and had a strong financial position, despite having lost market share to Japanese firms;
- The firms already were organized under the Semiconductor Industry Association (SIA) to address their common situation;
- They were able to employ a national security rationale under the auspices of the Defense Science Board; and
- They were able to focus on a mutually agreed production process (CMOS) and a relatively predictable, although challenging, production roadmap based on the extension of Moore's Law.

Not all these elements will necessarily pertain to other electronics technologies, such as optoelectronics and MEMS, or other advanced technologies, such as nanotechnology. Moreover, SEMATECH came into being just prior to nearly complete economic globalization and was able to ride a national competitiveness push as well as a national security wave to success. After nearly 10 years, SEMATECH abandoned the national perspective by reforming as an international entity.

SEMATECH demonstrated that fiercely competitive firms—which had not been able to agree upon, let alone address, mutual interests in improved manufacturing processes—could find a way to cooperate and collaborate for their general benefit and for the benefit of their underlying supply infrastructure.

Advanced Technology Program

The Omnibus Trade and Competitiveness Act of 1988 created the Advanced Technology Program (ATP) at the National Institutes of Standards and Technology, Department of Commerce. This "Trade Act" represented a shift from a focus solely on mission-related (e.g., defense) R&D to one that encompassed technology development and improving the quality and cost of manufacturing. Initiated as a pilot program in 1990, the Omnibus Trade and Competitiveness Act of 1988 directed ATP to support U.S. companies by "…creating and applying the generic technology and research results necessary to: (1) commercialize significant new scientific discoveries and technologies rapidly; and (2) refining manufacturing technologies."

The Act further specified that joint ventures were to be allowed and that funding was to be through cooperative agreements with U.S. businesses.

ATP provided *cost-shared* funding to companies of all sizes to accelerate the development and broad dissemination of high-risk technologies that promised significant commercial payoffs and large social benefits for the nation. The ATP program encouraged industry to undertake higher risk projects than they would have pursued otherwise. These efforts are typically in a stage of development that is too early or too risky to find private-sector support.

From 1990 to 2007,[11] ATP received nearly 7,000 proposals from all sectors of industry, and funded 768 awards with more than 1,500 participants. A unique feature of the ATP was its peer-reviewed selection process based on technical *and* business criteria. Few other government programs include business criteria as a requirement for

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[11] The America COMPETES Act (H.R. 2272), passed on August 9, 2007, abolished the Advanced Technology Program (ATP). Separately the statute created the Technology Innovation Program (TIP). For more information about this program, see: http://www.nist.gov/tip/.

funding. While the ATP funding could be used only for technology development and not for the business side of the project, the criteria still required that the business plan and potential economic benefits be a significant component for selection.

Scientists and engineers from NIST and other Federal laboratories completed the technical reviews. Business consultants with significant industry experience completed the business reviews for each proposal.

ATP used two formats for its proposal solicitations:[12]

- General competitions were held every year from 1990 to 2007 and were open to any area of technology.
- Technology-focused competitions were held between 1994 and 1998. ATP developed seventeen technology-focused areas where specific technology-sector investments were considered. These areas were defined by working with industry through public forums. Nine of these areas were in the manufacturing sector,[13] specifically the following areas:
  - Manufacturing Composite Structures (1994 and 1995),
  - Materials Processing for Heavy Manufacturing (1995),
  - Motor Vehicle Manufacturing Technologies (1995 and 1997),
  - Catalysis and Biocatalysis Technologies (1995 and 1998),
  - Technologies for the Integration of Manufacturing Applications (1995 and 1997),
  - Microelectronics Manufacturing Infrastructure (1998),
  - Photonics Manufacturing (1998),
  - Premium Power (1998), and
  - Selective-Membrane Platforms (1998).

ATP made awards to either a single company or joint venture collaborations. The projects had to be led by for-profit companies but could include universities, other businesses, and other research organizations. The company or companies covered all indirect research costs, and could contribute to the direct research costs. A joint venture award provided co-funding for two or more U.S. incorporated for-profit companies and could include subcontractors, non-profits, and independent research organizations. While there was no dollar limit on the ATP share of the award, the joint venture was required to cover more than half the project costs and could run for up to 5 years.

ATP was a controversial program from the start, which was reflected in ups and downs of its annual budget. The ATP was a target for several reasons:[14]

- *ATP suffered from variable budget support.* The Clinton administration made the ATP a focus of their civilian technology program and its budget grew from 1992 to 1995. The decline in the budget in 1995–1996 is a reflection of the shift in parties in Congress from the Democratic Party (who supported ATP) to the Republican Party (who generally opposed it).
- *ATP was a national program.* As a result, it could not develop a large presence in many states,[15] resulting in minimal political support.
- *ATP funded U.S. subsidiaries with foreign parents, with the requirement that research and commercialization would be conducted in the United States.* However, opponents believe that the United

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[12] National Institute of Standards and Technology, *Enhancing America's Manufacturing Competitive: A Review of the NIST ATP Investments in Manufacturing Technologies*, Gaithersburg, MD, 2007. http://www.atp.nist.gov/clso/mfg_paper_2006_01_24_full_version.pdf [last accessed February 20, 2010].

[13] National Institute of Standards and Technology,. *Previously Competed FOCUSED PROGRAMS (1994-1998)*. Gaithersburg, MD, 2007, available at http://www.atp.nist.gov/atp/focus1.htm [last accessed on February 20, 2010].

[14] Based on Christopher T. Hill, "The Advanced Technology Program: Opportunities for Enhancement," in *Investing in Innovation*, Lewis M. Branscomb and James H. Keller (eds), MIT Press: Cambridge, MA, 1998.

[15] The exception to this was the concentration of ATP projects in Silicon Valley, CA, the Route 128 corridor in Boston, and in Austin, TX.

States should not fund any foreign-owned companies, even if they have a large presence in the United States (e.g., Michelin Tires in South Carolina).

- *ATP funded large companies.* Proponents argue that some of the highest risk research can be undertaken only by large companies who have access to resources. They also argue that there are entrepreneurs in these large companies who are competing for funds similar to small business entrepreneurs. Opponents argued that this was "corporate welfare."
- *ATP funded single companies as well as joint ventures.* Some argue that government funds should not be used to help one firm compete against other firms. However, ATP often funded many companies to focus on a technology area and each took a different approach.
- *Universities could not lead projects.* Universities were allowed to participate in single company projects as subcontractors, and as partners or subcontractors in Joint Ventures (but not lead).[16] Proponents believed that the ATP awardees should focus on developing technologies that are likely to be commercialized. However, over half of ATP projects were based on ideas (either through spin-offs directly from the university or through licensing), so there were strong synergies with universities;
- *The Technology Innovation Program replaced ATP by in 2007.* While there are many similarities between the two programs, the Technology Innovation Program does not require that the proposal demonstrate the potential for economic benefit. The focus is solely on solving technical and "societal" challenges.[17]

Other Public-Private-Partnerships

There are many examples of U.S. and foreign public-private partnerships. This section briefly describes a few such partnerships.

Semiconductor Research Corporation (SRC)[18] was founded in 1982 as a semiconductor industry consortium to manage university research performed on behalf of its members. Since its inception, SRC has invested over $1.1 billion in research supporting over 7,000 students at over 200 universities worldwide.[19] SRC research is pre-competitive and the results are shared among the members. Federal partners providing funding for SRC research include DARPA, NIST, and NSF. State and local governments provide infrastructure and other support.

SRC operates three research programs covering a wide range of time horizons:

- **Global Research Collaboration (GRC):** research undertaken through the GRC has a 7- to 14-year implementation timeframe and focuses on traditional silicon-based semiconductor research challenges. Industry is strongly involved in formulating, shaping, and executing these research programs. An Engineering Research Center for Environmentally Benign Semiconductor Manufacturing is also funded under a GRC/SEMATECH partnership.
- **Focus Center Research Program (FCRP):** research undertaken through the FCRP has a 14 - to 20-year implementation timeframe and is strongly university-directed. This research aims to reach the ultimate scaling limits of silicon-based semiconductors. The FCRP centers are virtual centers, each with an annual budget of approximately $7 million used to address one of the technology focus areas of the International Technology Roadmap for Semiconductors (ITRS).
- **Nanoelectronics Research Initiative (NRI):** research undertaken through the NRI has an implementation timeframe of 20 years or more. Research under the NRI is discovery-oriented and is primarily focused on identifying technologies that can sustain growth in performance "beyond Moore's Law." Projects under NRI are organized into multi-university centers and at NSF-funded nanoscience centers.

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[16] The Technology Innovation Program allows universities to co-lead a joint venture.

[17] See http://www.nist.gov/tip/revised_faq_website_1_7_2010.pdf.

[18] *University-Private Sector Research Partnerships in the Innovation Ecosystem*, Appendix A, PCAST, 2008.http://www.whitehouse.gov/files/documents/ostp/PCAST/past_research_partnership_report_BOOK.pdf [last accessed 21 February 2010].

[19] See "About Semiconductor Research Corporation," http://www.src.org/member/about/src.asp.

College of Nanoscale Science and Engineering (CNSE)[20] is the first college in the world dedicated to nanoscience, nanoengineering, nanobioscience, and nanoeconomics. Its Albany Nanotech Complex began operations in June 1997 with the opening of the NanoFab 200, a 70,000 square foot, $16.5 million nanotechnology research and development center. The complex gradually expanded into a $5.5 billion, 800,000 square foot facility, with 80,000 square feet of clean room space. The Albany NanoTech Complex provides a centralized facility for focused nanoscale research at a range of technology development levels, from basic research to product development, including pilot manufacturing and rapid prototyping capabilities.

Partners of CNSE are quite diverse. The complex has more than 250 global corporate partners, including IBM and SEMATECH; it receives funding from the State of New York and a number of Federal Government laboratories and agencies, including NIST; and it collaborates with universities including Harvard, Yale, MIT, and Georgia Tech. CNSE also works with a range of K-12 school districts to provide nanoscale education programs, and has doctoral, maters, and dual degree (Nano plus MBA) programs. Technology foci among these partners extend over biomedical, energy, environment, defense, transportation, telecommunications, and consumer applications. Partnerships range from R&D consortia lasting 10 or more years to short-term collaborations between CNSE and individual corporations or universities.

Advanced Research Projects Agency-Energy (ARPA-E) of the Department of Energy was launched to fund projects that are high risk and, if successful, will produce disruptive transformational technologies. The program is modeled on the Department of Defense's DARPA program. ARPA-E was authorized in the 2007 America COMPETES Act and started in 2009. ARPA-E is considered a PPP, in part, because it requires cost sharing (10 percent for universities and other institutions of higher education; 20 percent for all other applicants, although a 50-percent match may be required in special circumstances).[21]

ARPA-E's focus is on producing outcomes that will address U.S. climate and energy security objectives.[22] ARPA-E funds a variety of projects that span from applied research to prototype/demo stages. ARPA-E does not fund basic research projects nor projects that will take longer than 5 years, lead to incremental improvements, or are large-scale commercial demonstrations. In its first solicitation, ARPA-E received almost 3,700 concept papers. After reviewing these papers, the program administrators encouraged 312 proposers to submit a full application. From this pool, 37 projects were funded in October 2009. The average funding for each project is $4 million for a period of 2 to 3 years.

ARPA-E takes a systematic approach to selecting topics for future solicitations. First they seek public input through a formal process, requesting ideas for programmatic areas, scientific opportunities, and on technical barriers to the development of technology that has potential to be commercialized. Next, they seek more detailed input through a series of focused workshops on potential program areas. The most recent set of workshops were held in fall 2009 and focused on grid scale energy storage, energy storage for vehicles, direct solar fuels, and carbon capture and sequestration.

The ARPA-E website notes that "If just a fraction of the projects funded by ARPA-E are successful in reaching the marketplace, the U.S. will benefit greatly by creating new industries and jobs, making energy technologies

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[20] See "CNSE's Albany NanoTech Complex," available at http://cnse.albany.edu/facilities/albany_nanotech.html [last accessed 1 March 2010] and University-Private Sector Research Partnerships in the Innovation Ecosystem, Appendix A, PCAST. 2008, http://www.whitehouse.gov/files/documents/ostp/PCAST/past_research_partnership_report_BOOK.pdf [last accessed 21 February 2010].

[21] Summary of ARPA-E Funding Opportunity announcement #2, http://www.lanl.gov/source/orgs/tt/arpa-e/pdf/arpa-e_foa2_summary.pdf [last accessed on March 2, 2010]. In addition to the cost share percentage, the match can be funds-in or in-kind effort, the awardees share must be from non-Federal sources, and the applicant must account separately for costs applied to ARPA-E and other Federal programs.

[22] This section is primarily from http://arpa-e.energy.gov/portals/0/Documents/ConferencesandEvents/Pastworkshops/ElectricalEnergyStorage%20forVehicles/Danielson.pdf [last accessed on February 21, 2010].

substantially more cost-saving and profitable, and accelerating the timeframe for achieving energy and climate goals."[23]

ARPA-E is similar to the NIST Technology Innovation Program. Both programs view commercialization as an outcome but do not require companies to include their commercialization plans in their proposals. DARPA has a ready customer, the Defense Department. Although they are mission-focused, it is not clear that ARPA-E and TIP have ready customers.

Partnership for a New Generation of Vehicles (PNGV) of the Department of Energy was established in 1993. This cooperative research effort involved seven government agencies, the United States Council for Automotive Research (USCAR), DaimlerChrysler Corporation, Ford Motor Company and General Motors Corporation. (USCAR was formed in 1992 by Chrysler, Ford, and General Motors to leverage the companies' research efforts in non-competitive areas.) The U.S. Department of Energy was a major participant in PNGV.[24] The most well-known goal of the partnership was to develop technology that could be used to create vehicles that could achieve up to triple the fuel efficiency of vehicles in 1993 with very low emissions, but without sacrificing affordability, performance, or safety. The auto manufacturers met a major partnership milestone by introducing their concept vehicles in early 2000.[25]

The partnership was successful in increasing the profile of the advanced technology opportunities and it led to improved working relationships between the automakers and the Federal Government.[26] "It also indirectly led to technology advancement by inspiring more aggressive investments by European and Japanese automakers that, in turn, through a boomerang effect, inspired U.S. automakers to do likewise."[27] The program was terminated in 2003.

Fraunhofer Gesellschaft (FhG) [28] is a German applied research consortium comprised of over 80 research institutions, 59 of which are in Germany. FhG was founded in 1949 as a mostly administrative organization aimed at raising and distributing funds that would revitalize Germany's research infrastructure and industry, but it quickly began opening its own research institutions. In 1972, the "Fraunhofer Model" was developed: state funding of Fraunhofer Institutes is directly tied to the size of FhG's private contracts. This ensures that the Institutes maintain their leadership in areas of research that are relevant to industry, while simultaneously guaranteeing freedom to be forward-looking. The institutes now receive roughly 40 percent of their funds from the public sector, to be used for pre-competitive research, and 60 percent from private industry contracts.

The Fraunhofer Institutes are organized into seven topical Fraunhofer Groups: Defense and Security, Information and Communication Technology, Life Sciences, Materials and Components, Microelectronics, Production, and Light and Surfaces. The institutes participate in more loosely organized and technology-centered Alliances, such as the Nanotechnology and Energy Alliances that create points of contact for industry. Fraunhofer Institutes also take part in several regional innovation clusters that bring together industry, university, and non-university research institutes to collaborate within a technology space.

Although the Institutes do not have specific technology transfer offices, leading researchers are expected to be able to find customers for Fraunhofer technologies. Access to and (in some cases) ownership of FhG intellectual

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[23] See http://arpa-e.energy.gov/About.aspx.

[24] See http://www1.eere.energy.gov/vehiclesandfuels/facts/favorites/fcvt_fotw128.html [last accessed March 2, 2010].

[25] See http://www1.eere.energy.gov/vehiclesandfuels/pdfs/success/pngv3_23_01.pdf [last accessed March 2, 2010].

[26] National Research Council, *Review of the Research Program of the Partnership for a New Generation of Vehicles: Seventh Repor*t, 2001, available at http://www.nap.edu/catalog/10180.html.

[27] Daniel Sperling, "Public –Private Technology R&D Partnerships: Lessons from US Partnership for a New Generation of Vehicles, *Transport Policy*, 2001, pp. 247–256.

[28] See Fraunhofer-Gesellschaft at http://www.fraunhofer.de/en [last accessed 1 March 2010] and PCAST, University-Private Sector Research Partnerships in the Innovation Ecosystem, 2008, Appendix A, available at http://www.whitehouse.gov/files/documents/ostp/PCAST/past_research_partnership_report_BOOK.pdfl [last accessed 21 February 2010].

property is granted to industry partners based on the degree to which partners contributed to the financing of center-based research.

IMEC[29] is a non-profit, independent research center that was founded by the state government of Flanders, Belgium, to perform next-generation electronics research to stay 3 to 10 years ahead of industry needs. Its current focus is on nanoelectronics, nanotechnology, design methods, and information and communication technologies. It employs 1,650 researchers, including over 550 industrial residents and guest researchers. Over half of IMEC's funding is from international industrial partners, 20 percent is from Flemish industry, and 15 percent is from the European Community, the European Space Agency, and the Flemish government.

IMEC collaborates with and transfers technology to outsiders through several mechanisms.[30] The IMEC Industrial Affiliation Programs (IIAP) is based on a model of sharing intellectual property and talent, risk, and cost. Partners send researchers to work with the IMEC team, and results that are more generic can be shared between partners in a program. IMEC also carries out bilateral collaborations for more focused development-oriented work, often with small- to medium-sized enterprises. IMEC generally maintains ownership of its intellectual property, preferring instead to license full user rights to partners. In some cases, however, expertise is co-owned by IMEC and the industrial partner. IMEC also actively creates spin-off companies that are incubated with IMEC seed money, infrastructure, and staff support.

Conclusion

The role of Federal S&T programs, policies, and activities has been both to sustain and maintain technological capabilities and competencies in existing manufacturing areas—such as semiconductors—and to build new capabilities and competencies in emerging areas—such as optoelectronics, organic light emitting diode (OLED) displays, and advanced energy technologies. A major focus has been on the challenges of manufacturing in specific sectors and spurring innovation in these target sectors. Innovation in manufacturing lays the foundation for growth across a variety of sectors, and Federal S&T involvement can help to accelerate this growth.

This paper described three roles government has played in support of advanced manufacturing technologies. These include the role as an early investor, in which the government identifies promising industries to fund in later stages of the innovation process; as a leading customer, in which the government provides guaranteed first purchases for a product; and as a partner in Public Private Partnerships, in which the government jointly funds and operates projects that would not otherwise be initiated within any one sector alone. The role of R&D public-private partnerships (PPPs) is described in greater depth, since they are a well-established mechanism and are becoming more prevalent. The programs described have spanned many sectors and approaches, including SEMATECH, the Advanced Technology Program, and the Fraunhofer Institutes and IMEC in Europe.

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[29] See http://www2.imec.be/be_en/home.html [last accessed 1 March 2010]; PCAST. 2008. University-Private Sector Research Partnerships in the Innovation Ecosystem. Appendix A, available at http://www.whitehouse.gov/files/documents/ostp/PCAST/past_research_partnership_report_BOOK.pdf [last accessed 21 February 2010].

[30] IMEC, *08 Annual Report*, http://www2.imec.be/content/user/File/Annual_report2008.pdf [last accessed 1 March 2010].

Question 5: What Federal Government science and technology programs or policies, if any, should be put into place to accelerate the development and adoption of advanced manufacturing technologies by industry? How might the government encourage increased funding for pre-competitive research by industry?

In the case of advanced manufacturing technologies, government support of research and commercialization pathways can accelerate the development and adoption of advanced manufacturing technologies by industry.

Historically, the Federal Government has often supported science and technology through funding of basic research at the science agencies. At the same time, one could argue that the current Federal system for funding research pays comparatively scarce attention to technology commercialization. Although examples of Federal commercialization activities exist (e.g., DOD's research and development through to acquisition), technology development outlets for Federal research are limited.

Any government strategy that would limit funding to basic research alone rests on the economic assumption that once knowledge is revealed it will be applied and developed into commercial products by industry. However, this assumption simplifies the process of innovation by ignoring significant barriers to the translation of science into technological and, ultimately, economic gain. Industry alone may lack the incentive or ability to develop basic research further due to such factors as extreme technological uncertainty, high public-goods content, institutional inertia, coordination and communication challenges, lack of funding for proof-of-concept research and other impediments to commercialization that are often referred to as the "valley of death". As a result, new research lacking an immediately viable commercial application often never has the chance to make it to market due to an absence of development funding, whether public or private.

Government may choose to implement one of several possible policy approaches to support U.S. manufacturing and technology. At the most basic level, research provides the foundations for private technology development and commercialization. Broader coordinated science and technology policies and programs can facilitate the technology development process from research through to adoption. Comprehensive approaches to manufacturing and technology policy extend into other areas relevant to U.S. economic competitiveness.

Manufacturing and Technology Policy: Three Illustrative Examples

The 1988 Omnibus Trade Act, the 2007 America COMPETES Act, and the Department of Energy (DOE) portfolio of programs each provides a different mix of approaches that could inform future manufacturing and technology policy. The first two offer historical examples of legislation generated in response to concerns about declining U.S. competitiveness. The third example describes one agency's systematic approach to technology development and adoption.

Legislative Responses

The **1988 Omnibus Trade Act** provides one historical example of a comprehensive science and technology policy approach. Reacting to rising international competitive pressures, this "Trade Act" created a portfolio of programs with a focus on technology development and manufacturing to improve the balance of trade and increase the market shares of the U.S. manufacturing sector. It resulted in the following actions:

- The National Bureau of Standards became the National Institutes of Standard and Technology (NIST), and its mission was broadened to focus on manufacturing and technology.

- The Advanced Technology Program, Manufacturing Extension Program, and the Malcolm Baldridge National Quality Award were created as extramural programs at NIST to accelerate, support, and encourage manufacturing innovation and actions to improve productivity.

- The Technology Administration was set up at the Department of Commerce to oversee these new programs and to conduct studies on innovation and manufacturing.
- The legislative response tackled the debate from many angles, recognizing that effective legislation would require a broad understanding of the role of technology and manufacturing to include a focus on technology commercialization, worker training, business support, and trade policy.

Like the 1988 Trade Act, the **America COMPETES Act of 2007** responded to concerns that the United States was compromising future economic competitiveness by inadequately funding science and technology. The act is based on the premise that scientific and technological innovation is necessary to remain competitive in an increasingly globalized economy. The legislation addresses this challenge by targeting the primary inputs to the innovation-driven economy: science, technology, engineering, and mathematics (STEM) education and early stage basic and applied research. Specifically, the America COMPETES Act:

- Supported science and engineering and STEM education from kindergarten through postdoctoral studies.
- Doubled funding for the physical sciences at the National Science Foundation, DOE's Office of Science, and the National Institutes for Standards and Technology over a period of 7 years.
- Created the Advanced Research Projects Agency—Energy within the Department of Energy to support high-risk energy technology projects.
- Replaced NIST's Advanced Technology Program (ATP) with the Technology Innovation Program (TIP).

Although the bill focused broadly on U.S. economic competitiveness, many of the identified drivers of future economic success also apply to manufacturing competitiveness, particularly for advanced manufacturing.

An Agency Approach

The Department of Energy has established a number of complementary programs designed to bridge the gap between the early-stage science and final commercialization of new energy technologies, while reorganizing some existing programs to directly complement the new programs. The current set of DOE programs may provide a useful model for developing a portfolio of manufacturing programs across the board from basic science through commercialization.

The DOE programs listed below demonstrate the variety of potential agency strategies across the invention to innovation life cycle (see Table 5-1). The following examples may serve as a useful conceptual approach for tackling common goals to modernize American manufacturing.

Table 5-1: Department of Energy's Portfolio Approach to Accelerate the Invention to Innovation Process

<table>
<tr><th>Fundamental Science</th><th>Applied Science</th><th>Technology Development</th><th>Technology Integration and Economic Feasibility</th><th>Pilot Projects</th><th>Deployment/ Commercialization</th></tr>
<tr><td colspan="2">Energy Frontier Research Centers (EFRC)</td><td colspan="4"></td></tr>
<tr><td colspan="4">Energy Innovation Hubs (EIH)</td><td colspan="2"></td></tr>
<tr><td></td><td colspan="4">Advanced Research Projects Agency—Energy (ARPA-E)</td><td></td></tr>
<tr><td colspan="2"></td><td colspan="4">Industrial Technologies Program (ITP)</td></tr>
<tr><td colspan="2"></td><td colspan="4">Building Technologies Program (BTP)</td></tr>
<tr><td colspan="4"></td><td colspan="2">Innovative Technology Loan Guarantee Program</td></tr>
</table>

These programs each possess management structures designed around specific ends, and they vary extensively in size, aim, and activity. See Appendix 5-A for more details on these programs.

Policy Prescriptions beyond Science and Technology Programs

By enabling the pathway to commercialization, comprehensive approaches to Federal science and technology policy and programs aim to ensure that technological benefits accrue from earlier investments and breakthroughs in basic science. However, the source of production and the distribution of those benefits between nations and across society depend heavily on complementary economic and social policies. Moreover, globalized competition increasingly weakens the link between business location and customer base, allowing networked, multi-national firms to locate production activities according to cost and capabilities. For the United States to remain competitive as a location for economic activity, whether in manufacturing or other industries, public policy must address the fundamental cost drivers and their interrelationships. This view considers recommendations concerning tax rates and trade policies to be as important to the future of U.S. manufacturing as STEM education and research and development (R&D) commercialization pathways.

As a first step towards understanding which of those issues are most important to manufacturing specifically, we examined nine reports in support of U.S. manufacturing and synthesized their recommendations. (See Appendix 5-B for a list of the nine reports). The reports are authored by various sources in government, academia, industry associations, think tanks, and advocacy groups While each report reflects a different perspective and focus, all attempt to provide critical insight into the principal policy issues concerning current challenges facing U.S. manufacturing. By providing a common organizational framework, this summary seeks to elucidate the main points of convergence among the reports while providing an easy reference for comparing different options.

This analysis uses the Executive Office of the President's *A Framework for Revitalizing American Manufacturing* as an organizational starting point. The document, released in December 2009, notes that "in order to understand the appropriate role for government to support manufacturing and capture its positive social impacts, it is necessary to identify each cost driver in the manufacturing process." Subsequently it identifies seven main drivers: labor force, technology and business practices, equipment, location, transportation, market access, and regulation and taxation. These seven cost drivers cover the issues that would be relevant to design of an integrated approach to promoting American manufacturing in the twenty-first century.

We extracted each report's recommendations and matched them to one or more cost drivers (see Table 5-2). Recommendations were then further sorted into subgroupings under each main driver according to shared characteristics, and policy planning was added as an eighth, cross-cutting category.

The following sections summarize the recommendations relating to each driver and subgrouping.

Labor Force

Labor Force includes any recommendations related to education, worker training, and health care and benefits. Overall, six of the nine reports make recommendations concerning labor. All six mentioned education in some form, ranging from strengthening K-12 schools to improving college affordability. These reports mention critical shortcomings in STEM education (science, technology, engineering, and math). In addition, at least two reports advocated revision of existing visa policies for foreign students. Four of the nine reports suggest ways of encouraging worker training, either on the job or for the unemployed. A different set of four reports address health care and benefits. Aside from a single call for pension reform, all of the recommendations attack the general problem of rising health care costs, albeit while advocating vastly different policy approaches. From supporting community colleges to reducing the cost of health care, a broad array of inputs is implicit in the costs and considerations of firms.

Table 5-2: Counts of Recommendations by Manufacturing Report and Topic

Topic of Recommendations/Report	EOP	DOC	EPI	iTIF	NAM	NDU	Pisano	Popkin	Tassey	Grand Total
Access to Markets	8	17	2		1	4		2		34
Enforce Trade Agreements / Prevent Unfair Competition	1	7	2	0	1	4	0	1	0	16
Open Foreign Markets	1	5	0	0	0	0	0	0	0	6
Promote American Exports	5	5	0	0	0	0	0	1	0	11
Policy Planning	1	0	0	0	0	0	0	0	0	1
Equipment	8	0	1	3	0	0	1	2	0	15
Clean Technology Investment	5	0	1	3	0	0	0	1	0	10
Financial Regulation	3	0	0	0	0	0	1	1	0	5
Labor	10	9	5	0	3	1	0	3	0	31
Education	6	1	1	0	2	1	0	2	0	13
Health Care and Benefits	1	5	1	0	1	0	0	0	0	8
Training	3	3	2	0	0	0	0	1	0	9
Policy Planning	0	0	1	0	0	0	0	0	0	1
Location	4	1	0	1	0	1	0	2	0	9
Cluster Development	1	0	0	1	0	1	0	2	0	5
Community Support	3	1	0	0	0	0	0	0	0	4
Regulation and Taxation	2	16	2	0	4	0	0	2	0	26
Legal System	0	5	0	0	1	0	0	0	0	6
Regulatory Compliance	0	5	1	0	2	0	0	0	0	8
Tax Structure	1	3	1	0	1	0	0	2	0	8
Policy Planning	1	3	0	0	0	0	0	0	0	4
Technology and Business Practices	11	12	3	3	2	1	1	3	5	41
Intellectual Property	1	1	1	0	0	0	0	0	0	3
Public-Private Partnerships	2	6	2	0	0	1	0	1	0	12
Research and Development	5	3	0	2	2	0	1	1	2	16
Policy Planning	3	2	0	1	0	0	0	1	3	10
Transportation	7	2	1	0	1	0	0	1	0	12
Infrastructure Provision	6	1	1	0	0	0	0	1	0	9
Policy Planning	1	1	0	0	1	0	0	0	0	3
Policy Planning Total	6	11	2	1	1	1	1	2	3	28
Grand Total	50	62	15	7	11	8	3	16	5	177

Technology and Business Practices

Technology and Business Practices contain more total recommendations than any other category, and it is the only category for which all nine reports made at least one applicable recommendation. Many of the previously discussed science and technology policies fall under this driver, including R&D, intellectual property, and public-private partnerships. Seven of the nine reports mention policies in R&D, which include both direct public investments through agency granting processes and incentives for private research. Three reports explicitly advocate reform and expansion of the existing research and development tax credit. Several reports also favor focusing R&D activities on particular goals, such as clean energy or communications technologies. A number of recommendations target programs like the Manufacturing Extension Partnership (MEP), which provide support and technical assistance for particular industries. In addition, several reports call for enhanced collaboration between Government, academia, and industry on technology transfer, standards, and joint investments. Recommendations in support of public-private partnerships to encourage technology transfer and commercialization of R&D take on a variety of different forms and are mentioned by five of the nine reports. Intellectual property issues surface in three of the nine papers, primarily in the general need for patent reform.

Equipment (Capital Investment)

Six of the nine reports make recommendations regarding equipment, which refers here to the cost of capital investment. Equipment recommendations are split into general financial regulation and directed clean technology investment. Three reports make recommendations for improving financial market functioning, noting the strong link between the strength of the manufacturing sector and the health of our financial system. Four push targeted tax incentives, cash grants, and loan programs for new clean technology investments.

Location

Location-focused recommendations primarily include cluster development strategies, which favor geographic concentration of like skills and industries, as well as community support, for localities that have lost their particular niche. Four reports focus on cluster development as an economic strategy to enhance competition, specialization, and efficiency for greater overall innovation. Just two reports additionally point out the corresponding need to reinforce the social safety net for communities, noting that specialized local and regional economies are substantially exposed to sector-specific risks (e.g., Detroit and the automotive industry).

Transportation

Transportation as a driver encompasses critical infrastructure to transport goods, energy, people, and information. Four reports emphasize the importance of the nation’s energy infrastructure and affirm the importance of physical infrastructure development in general. Examples of specific recommendations concerning infrastructure include air traffic control, broadband, high-speed rail, clean city infrastructure, and modernizing the electric grid.

Access to Markets

Five of the nine reports make recommendations regarding access to foreign markets. This category contains the second largest number of total recommendations, which focus on enforcing trade agreements and preventing unfair competition, opening foreign markets, and promoting American Exports. Six reports argue for fair competition in international trade with regard to enforcing trade agreements and preventing unfair competition. The reports specifically cite distortions caused by subsidies and tariffs, currency manipulation, and other forms of protectionism, with China singled out. Three reports identify detailed mechanisms by which the U.S. could promote exports through financing, expertise, or regulatory changes (e.g., reviews of export control laws). Only two reports contained calls for opening new markets abroad. Other issues raised include intellectual property enforcement and the role of labor and environmental standards in trade agreements.

Regulation and Taxation

Five of the nine reports make recommendations principally concerning regulation and taxation. This category includes proposed changes in overall tax structure, regulatory requirements, and the legal system. Most tax-focused recommendations target the corporate income tax, which several reports noted was significantly higher than that of competing economies. Other recommendations focused on more detailed issues, such as lowering the costs of tax compliance, reforming policies on repatriation of foreign-earned profits, and favorable tax treatment for employee-owned companies. With regard to regulation, a few reports comment on pollution abatement costs, while others use regulatory reform as a proxy for other aims. For instance, one report calls for strengthening the Consumer Product Safety Commission (CPSC) in response to reported health hazards from certain imported goods. A few reports also recommend legal reforms focused on liability to reduce the disincentives to invest in manufacturing.

Policy Planning

Most of the reports made recommendations linked to formation of Federal policies in support of manufacturing. A number of recommendations fall under policy planning proposals, some overlapping with the seven cost drivers and some not tied to another particular section. Policy planning spanned recommendations for new Government bodies focused on manufacturing to prioritization of research and funding.

Conclusion

As seen through three illustrative examples and nine reports, the manufacturing sector is a complex system, consisting of many different interacting parts impacted directly and indirectly by both general and targeted public policies. Comprehensive public policy must therefore approach manufacturing as part of a system that integrates design, services, production, and business innovations. Increasingly, manufacturing is performed by a network of global partners, comprised predominantly of highly specialized firms of small and medium size: “Supply chains are becoming supply networks; markets are becoming multidimensional, geographically and culturally.”[1] For example, offshoring of manufacturing activity may imperil the domestic research base as well, reducing incentives for companies to fund and conduct R&D activities in the United States. [2] While much of the value-added from the production of advanced technologies may not occur in the manufacturing step of the process, physical proximity to the manufacturing location may be required to maintain competitiveness in higher value-added activities. The first-mover advantages in advanced manufacturing technology development and deployment are significant, and encouraging both through science and technology policies can improve domestic manufacturers’ competitive situation relative to the rest of the world. However, since the competitiveness of U.S. manufacturers is affected not only by leading-edge technologies, but also by relative costs and capabilities, strategies such as those discussed above for promoting advanced manufacturing also address issues of general economic competitiveness**.** Effectively formed public policy to support manufacturing will address the whole innovation life cycle based on a broad view of the factors that affect U.S. manufacturing.

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[1] Lewis Branscomb. “Research Alone Is Not Enough,” *Science,* 15 August 2008: Vol. 321. no. 5891, pp. 915–916.

[2] Erica Fuchs. “The Impact of Offshore Manufacturing on Technology Competitiveness: Implications for U.S. Policy.” Presentation at the Science and Technology Policy Institute, February 2, 2010.

Appendix 5-A: Department of Energy Technology Life Cycle—Selected Programs

Table 5-A provides details on the selected DOE technology life cycle programs described below.

Energy Frontier Research Centers (EFRC)—Each center, run by 6–12 senior investigators, pursues “use-driven” fundamental research addressing an identified basic research need. The EFRC are funded through relatively small, $2 million to $5 million annual grants sustained over a period of 5 years.

Energy Innovation Hubs (EIH)—Hubs are larger, multi-institutional and multi-disciplinary pursuits organized through centralized science management practices, based off of successful historical examples (e.g., Bell Labs and the Manhattan Project). Work spans the range from applied research to development, engineering, and economic analysis supporting early-stage commercialization efforts.[3] Grants are approximately $22 million per year for 5 years, plus startup costs.

Advanced Research Projects Agency–Energy (ARPA-E)—This agency, modeled after the Defense Advanced Research Projects Agency (DARPA), pursues high-risk, high-payoff R&D directed towards near-term commercialization. One- to three-year Grants ranging from $0.5 million to $10 million are given to single investigators or small teams for work on energy technologies that are viewed as potentially transformative.

Industrial Technologies Program (ITP)—This program, run within DOE’s Office of Energy Efficiency and Renewable Energy (EERE), focuses on technology development to providing technical assistance and best practices information to industry to reduce industrial energy intensity.

Building Technologies Program (BTP)—Similarly, BTP, run by EERE, is organized around the goal of improving building energy efficiency. For buildings, this means addressing everything from R&D for building systems integration to energy codes and equipment standards. Since most buildings-related regulation is done at the local level, BTP provides intergovernmental technical and program-design assistance.

Innovative Technology Loan Guarantee Program—Funded under the Recovery Act, this program provides loan guarantees for large projects that avoid air pollution or greenhouse gas emissions, utilize new or significantly improved technologies, and offer a reasonable prospect of repayment. Loan guarantee amounts and terms vary according to project type, cost, and other characteristics.

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[3] In addition, for at least one of the three funded energy innovation hubs, DOE is experimenting with interagency collaboration to support an Energy Regional Innovation Cluster (E-RIC), which would provide complementary support to commercialization efforts in areas such as local technical training and economic development.

1 **Table 5-A. Department of Energy Technology Life Cycle—Selected Programs**

	Energy Frontier Research Centers (EFRC)	Energy Innovation Hubs (EIH)	Advanced Research Projects Agency—Energy (ARPA-E)	Industrial Technologies Program (ITP)	Building Technologies Program (BTP)	Innovative Technology Loan Guarantee Program
2011 Budget Request	$140 m	$141 m	$300 m	$100m	$231m	$500m**
Managing Office	Basic Energy Sciences	Board of Advisors (DOE leadership)	ARPA-E	EERE	EERE	Loan Guarantee Program
Focus	Accelerated "use-inspired" fundamental (basic and applied) research targeted to overcoming energy technology roadblocks	Cross-disciplinary collaboration on high-priority technologies from research to engineering and early-stage commercialization (Bell Labs model)	High-risk, high-payoff research directed towards near-term commercialization opportunities	Research, development, and deployment of industrial energy efficiency technologies and practices	Activities aimed at improving energy efficiency of building equipment, components, and systems and reducing building energy use	Accelerated commercial deployment and use of new or significantly improved energy technologies
Goals	Overcome specific scientific hurdles identified by Basic Research Needs report (e.g., novel materials for photovoltaics, thermoelectric waste heat recovery, and solid-state lighting).	Enable rapid commercialization of breakthrough ideas that industry is unlikely to pursue on its own (e.g., new catalytic materials and processes for artificial photosynthesis).	Accelerate research, development, and early-stage commercialization in critical areas for energy technology with potentially transformative effects.	Undertake program activities to reduce industrial energy intensity 25% by 2017 by changing the way industry uses energy.	Promote the development of marketable "net zero" energy homes by 2020 and commercial buildings by 2025.	Encourage clean energy projects that employ new or significantly improved technologies, and offer reasonable prospect of repayment
Grant Funding	$2–$5m per year	$25m per year	$0.5–$10m per year	-	-	-
Duration of Grant	5 years	5 years	1–3 years	-	-	-
Grant Recipient / Responsible Program	Groups of 6–12 senior investigators based at single- or multi-institutional university centers. Primarily university led.	Multi-investigator, multi-disciplinary, multi-institutional centers under a centralized management structure. Lead institution may be national laboratory, university, business, or nonprofit.	Single investigator, small groups, or small teams. May be business, university, nonprofit or a combination.	ITP, which sponsors cost-shared R&D and supports the use of today's advanced technologies and energy management best practices.	BTP, which funds R&D, assists with equipment standards and building codes, provides intergovernmental technical and program assistance, and works with building industry groups on initiatives and best practices in building energy efficiency.	Early commercial investors in innovative energy technologies.
Number of Program Areas	6	4	10	4	1	10

Detailed Program Areas	• Energy Supply (20 projects) • Cross Cutting (14) • Energy Storage (6) • Energy Efficiency (6) • New Materials* • Fundamental Science*	• Fuels from Sunlight • Efficient Energy Building Systems Design—Regional Innovation Cluster • Modeling and Simulation for Nuclear Reactors • Batteries and Storage*	• Building Efficiency • Carbon Capture • Direct Solar Fuels • Biomass Energy • Conventional Energy • Energy Storage • Renewable Power • Vehicle Technologies • Waste Heat Capture • Water	• Energy Intensive Industries • Cross-Cutting Technologies • Best Practices • Industrial Assessment Centers	• Appliances and Commercial Equipment Standards • Building America Homes • Building Energy Codes • Commercial Building Energy Alliances • Net-Zero Energy Commercial Building Initiative	• Biomass • Hydrogen • Solar • Wind and Hydropower • Advanced Fossil Energy Coal • Carbon Sequestration practices and technologies • Electricity Delivery and Energy Reliability • Alternative Fuel Vehicles • Industry Energy Efficiency Projects • Pollution Control Equipment

Appendix 5-B: Manufacturing in the United States: Reports Used in this Review

EOP: Executive Office of the President. “A Framework for Revitalizing American Manufacturing.” Washington, D.C. December 2009. Available at: http://www.whitehouse.gov/sites/default/files/microsites/20091216-maunfacturing-framework.pdf.

DOC: U.S. Department of Commerce. “Manufacturing in America: A Comprehensive Strategy to Address the Challenges to U.S. Manufacturing.” Washington, D.C. January 2004. Available at: http://www.trade.gov/media/publications/pdf/manuam0104final.pdf.

EPI: Susan Helper. “Renewing US Manufacturing: Promoting a High-Road Strategy.” Economic Policy Institute. Briefing Paper #212. Washington, D.C. February 2008. Available at: http://www.sharedprosperity.org/bp212/bp212.pdf.

ITIF: Rob Atkinson, et al. “Rising Tigers, Sleeping Giant.” Breakthrough Institute and Information Technology & Innovation Foundation. November 2009. Available at: http://www.itif.org/files/2009-rising-tigers.pdf.

NAM: The Manufacturing Institute. “The Facts about Modern Manufacturing.” 8th Edition. 2009. Available at: http://www.nam.org/~/media/0F91A0FBEA1847D087E719EAAB4D4AD8/Facts_About_Modern_Manufacturing.pdf.

NDU: National Defense University. *Manufacturing Industry*. Final Report. Industrial College of the Armed Forces. Fort McNair, Washington, D.C. Spring 2009. Available at: http://www.ndu.edu/icaf/industry/reports/2009/pdf/icaf-is-report-manufacturing-2009.pdf.

Pisano: Gary Pisano and Willy Shih. *Restoring American Competitiveness*. Harvard Business Review. July 2009.

Popkin: Joel Popkin and Kathryn Kobe. *Manufacturing Resurgence*. Prepared for the National Association of Manufacturers an*d* the NAM Council of Manufacturing Associations. January 2010. Available at: http://documents.nam.org/CMA/PopkinReport.pdf.

Tassey: Gregory Tassey. *Rationales and Mechanisms for Revitalizing U.S. Manufacturing R&D Strategies*. Journal of Technology Transfer. December 2009. Available at: http://www.nist.gov/director/planning/manufacturing_strategy_paper.pdf.

Question 6: What broad infrastructural improvements are critical for new versus existing enterprises? Where do public/private partnerships (PPP) play a crucial role?

Introduction

The Federal Government could initiate and support a variety of infrastructural improvements and programs to address, in part, gaps in the evolving requirements of both new and existing manufacturing enterprises to operate competitively. However, the needs of these enterprises vary from sector to sector and depend on whether the enterprise is an emergent or established firm attempting to develop and produce a new product line or an incumbent producing an existing product. Furthermore, the design, development, and production process of a manufactured good does not occur in isolation. Technical innovation is often iterative: (1) building upon previous technologies, processes, and knowledge, (2) dependent upon synergies between the design team, engineers, equipment producers, and systems integrators, among others, and (3) reliant upon an easily accessed sub-tier supplier network that can guarantee on-time delivery of components in sufficient quantity. These factors highlight the need to address the entire manufacturing supply chain and the entire technology life cycle in order to best support firms of all sizes at various stages of development and production.

Firms involved in the production of manufactured goods—from conception through development to commercialization—rely upon a number of processes and technologies to achieve success and maintain competitive advantage in the market. The speed at which firms are able to capitalize on innovation is perhaps the most critical aspect of competitive advantage in an increasingly globalized economy. Therefore, improvements to manufacturing infrastructure that accelerate the ability of firms in a sector (whether established or new) to bring incipient technologies to fruition are crucial enabling technologies that could be the focus of Government support. These underpinnings could provide capabilities beyond those that firms currently possess and allow them to overcome uncertainties and explore alternatives in the production of the potential goods. Incumbent firms with substantial existing revenues generally can acquire equipment by purchasing it, building it, or contracting for it, while expertise can be hired. This, however, is generally beyond the capacity of startup firms. Thus, providing an infrastructural base of expertise, analytical capabilities (including advanced computer modeling and simulation capabilities), and support for developing underlying tools, equipment, and processes, is potentially important to advance emergent technologies from conception into viable production.

As Greg Tassey notes, “while products commercialized based on new technologies are private goods, the underlying technology platforms (“generic technologies”) and supporting “infratechnologies” are derived from a combination of public and private assets.”[1] This observation is important for two reasons: (1) infrastructure is the foundation that commercialized technologies are built upon and enables their design, development, and production (2) the Government can play a role in fostering early investment in *under-supported* manufacturing infrastructure R&D, supply chain integration, manufacturing systems integration, and technology maturity life cycle management. Emerging firms that lack design support, tools, mature processes, and technical and business know-how must demonstrate some plan or ability to develop these to attract requisite start-up capital. Existing firms must constantly refine and renew the technology platforms they rely upon and manufacturing processes they employ in order to keep up with competitors, let alone capture competitive advantage. *Therefore, manufacturing infrastructure innovation is essential to both new and existing firms.*

An important mechanism for fostering and supporting the manufacturing infrastructure for both emerging and existing firms is the use of public-private partnerships (as detailed in Question 4), to enable the development of

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[1] Gregory Tassey. *Rationales and Mechanisms for Revitalizing U.S. Manufacturing R&D Strategies*, National Institute of Standards and Technology, 2009, available at http://www.usinnovation.org/files/RevitalizingUSManufacturingR&DStrategiesbyGTassey1209.pdf.

advanced manufacturing concepts, processes, tools ,and technologies and their rapid diffusion to innovative companies. In a globalized economy that demands flexibility and the ability of firms to rapidly assess the market, adapt to changing circumstances, and generate profits on smaller margins with evolving product lines, it is imperative that the United States maintain a techno-social ecosystem to support new and existing firms. This can be accomplished through investment in applied R&D toward the development of scalable, reconfigurable manufacturing processes and tools; access to cutting edge manufacturing systems integrators that leverage advances across the value chain to produce lean and efficient operations that cut down cycle time; and dissemination of organizational and business models and best practices.

The collaborative and cooperative interaction provided by public-private partnerships can allow firms to engage in R&D activities that would be too costly in time and investment for any individual firm to undertake, increasing the likelihood of generating breakthrough technologies and innovative practices, and promoting rapid knowledge transfer between partners. Furthermore, the companies that emerging and existing firms rely on in many areas of manufacturing generally are small and provide highly specialized equipment, specialty tools, materials, measurement, and testing. These smaller enterprises generally cannot afford significant investments in R&D. Public-private partnerships are one mechanism that allows firms, infrastructure companies, and sub-tier suppliers to form alliances and operate collaboratively and in a coordinated fashion.

Existing Enterprises

SEMATECH, as discussed in detail in Question 4 on public-private partnerships, is a specific example of the collaboration between the U.S. Government and a consortium broadly representative of the major players in the extant domestic semiconductor industry. SEMATECH was established to accelerate advanced manufacturing concepts to improve the competitiveness of domestic firms and retain market share in a highly competitive sector. SEMATECH established an experimental fabrication, where advanced processes and technologies could be developed using developmental materials, tools, and equipment from sub-tier suppliers. SEMATECH also served as a test integration facility for the tool and equipment suppliers, providing direct contact with its U.S. customers and the opportunity to be evaluated under a common set of production requirements. SEMATECH also allowed consortium member researchers to work on prototype production processes along with the SEMATECH staff, thereby promoting knowledge transfer and improving the competitive position of partner firms.

Thus, SEMATECH built upon a large, but disconnected, base comprised of the major players in the domestic semiconductor industry, and preserved it by resuscitating its manufacturing infrastructure.

New Enterprises

Is the “SEMATECH-model” appropriate and effective for firms engaged in the development of new technologies? SEMATECH’s establishment was based on some prior conditions that need to be considered. Specifically it had:

- A coherent industry group to galvanize support and provide the resources needed,
- A common overall production process, and
- A driving dominant product that creates an imperative for supporting the technology

The mechanisms for supporting new industries must recognize the fact that emerging companies often start from positions with little revenue, narrow technical expertise, and, usually, little experience actually making a product rather than performing research. Moreover, these emerging firms are highly unlikely to collaborate, since they are entrepreneurial enterprises attempting to develop new ideas into market-ready products in a time-sensitive and competitive environment. Therefore, establishing a consortium like SEMATECH for fundamentally new product areas could be difficult. For firms in such areas, just moving into a proof-of-concept level of production is daunting. What these firms often need is funding to take on the risky and uncertain development of production processes for a product that may itself be only a prototype. Incipient firms are often limited in production and process knowledge and investment capital while attempting to scale-up such limitations.

In today’s extremely tight capital market, investors shy away from ventures that involve the development manufacturing processes and/or facilities due to perceived risk. One mechanism to consider is a Government-supported “New Industries Investment Corporation” to provide early-stage capital investment for production facilities. This mechanism could be coupled with expertise or guidance, possibly through a panel of production experts and systems integrators that provides advice on manufacturing scale-up. The corporation could provide capital as long-term, low-interest loans that would be paid back proportionately or conditional to the new firm’s success.

The role of government in supporting new enterprises in the manufacturing process is generally portrayed as unusual and inappropriate. However, in many domestic industries, it is evident that the Federal Government was the key supporter that enabled new enterprises to move into successful manufacturing. The Federal Government can be the essential demand-driver for a new technology and provide alternative means to support the scale-up of production. This role is not limited to being an early customer, but also a customer who will pay upfront for products that are still unproven with a higher degree of risk than would private capital investment mechanisms. In essence, under the right conditions, government procurement contracts can be taken to the bank to get funding for manufacturing development. Moreover, the government can provide incentives to private capital investors to buffer their risks.

The Federal Government also has directly supported underlying materials and equipment manufacturing infrastructure when these have been judged to be impediments to the production of the new products deemed to be of national interest. This pertains to existing enterprises as well as new ones. For example, the DOD spent considerable funds advancing photolithographic tools, an existing technology, to advance the capabilities of the semiconductor industry when there were concerns that the unavailability of these tools would impede advances in integrated circuits (ICs). There were concerns whether the leading photolithography tools from Japan would be made available to U.S. IC firms as readily as to competing Japanese IC makers. In the early 1990s the development of new photolithography tools capable of half-micron and then quarter-micron line widths were judged to be crucial for maintaining U.S. competitiveness in ICs, and thus to national security, but unlikely to be developed by the IC device makers, since they were in the chip rather than tool business. However, the investments required were well beyond what individual lithography toolmakers could afford. To address this situation, the DOD, through DARPA, initiated an advanced lithography program that pursued the development of several alternative lithography tools (including x-ray lithography).

Another example of direct Federal support for an incipient manufacturing technology is the DOD Millimeter Microwave Integrated Circuit (MMIC) program. The focus of this program was the explicit development of manufacturing capabilities to reduce the cost of these devices for analog-digital conversion for signal processing, which was understood to be an intrinsically dual-use technology. The DOD was a leading edge customer and recognized that furthering the ability of firms to more efficiently produce these devices was in its interest. With costs reduced, these devices became a crucial factor in the development of cell phones.

The DOD has also supported manufacturing infrastructure through the Defense Production Act (DPA) Title III authorities to support the development and sustainment of key production facilities and processes based on national security needs. In electronics and sensing, these authorities were used to invest in production facilities, first for gallium arsenide, and then for indium phosphide crystal boules. In both cases, firms were unwilling to invest in the devices that required these materials, because of the lack of a reliable supply of high-quality materials (lack of impurities) needed. However, without willing customers to make devices from these materials, the materials firms could not attract investment to build the facilities and develop the processes needed to meet these needs—a classic “market failure.” The DOD used DPA authority to provide investment funds to break this holdup.

Conclusion

A question that needs to be addressed is whether emerging industries—nanotechnology, biotechnology, or another technology—face potential “market failures,” and whether the prospective value of the emerging industry is significant enough to warrant government involvement. Recently the DOD made a DPA Title III determination that scaling-up the production of nanotube-based carbon fiber composites requires support. How the Government determines which technology areas should be supported may be less clear than it was a decade ago, given the broad issues the U.S. economy faces in a highly competitive and globalized business environment dominated by multinational firms interlinked through complex networks of business and production relationships. National security has traditionally been, and still is, the primary lever for motivating Government support. However, emerging economic, energy and environmental security imperatives may also provide appropriate rationale for Government involvement in supporting manufacturing infrastructure for future industries.