MANUFACTURING PROSPERITY

A Bold Strategy for National Wealth and Security

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Offshore production in advanced manufacturing has reached a critical point in which the strategy of "invent here, manufacture there" has become "invent there, manufacture there." The United States must take bold steps to arrest this development and take advantage of transformational technologies to rebuild domestic manufacturing prowess for national wealth and security. These bold steps require a central national focal point with a comprehensive strategy, and significant and sustained public and private investments:

1. **Invest in translational research and manufacturing innovation**
2. **Encourage domestic pilot production and scale-up**
3. **Empower small and medium-sized manufacturers to deploy advanced technologies**
4. **Grow domestic engineering and technical talent**

Positive national impacts will justify the needed investments. The United States will

1. **regain fundamental manufacturing capabilities,**
2. **ensure a return on federal investments in R&D,**
3. **capitalize on technology changes broadly affecting manufacturing,**
4. **establish leadership in new industries of the future, and**
5. **restore the broad-based supplier networks that are essential to economic and national security.**

Because of a confluence of economic and technological forces, the United States now has an opportunity to rebuild its manufacturing base and restore its global competitiveness. But another report will not help. Bold steps commensurate with the scale and importance of the objectives are absolutely necessary. Implementing these bold steps requires a national focal point of responsibility with a comprehensive strategy and significant and sustained public and private investments. **Other countries are not standing still. The onus is on us.**

FOREWORD

American manufacturing faces both daunting challenges and transformative opportunities. Ensuring national security, preserving the nation's innovation edge, sustaining jobs, and maintaining global manufacturing leadership will require foresight, skillful cross-sector thinking, and serious investments.

In early 2018, MForesight: Alliance for Manufacturing Foresight conducted a series of roundtables with manufacturing experts, business leaders, and policymakers in cities across the United States. The objective was to gather perspective from multiple regions with industry clusters ranging from advanced technology sectors, such as electronics, biotechnology, and advanced materials, to large traditional, albeit still advanced sectors such as automotive, construction equipment, and food processing. Roundtables were held in Austin, Boston, Detroit, Indianapolis, Raleigh, San Jose, and Washington, D.C. To focus the discussion, participants were provided with information on trends in trade, value added, employment, foreign direct investment, research, start-ups, investment, and other key indicators on the state of U.S. manufacturing.

Roundtable discussions focused on several key questions:

1. **Regaining America's Industrial Commons:** What foundational capabilities are essential for the United States to regain a global leadership position and to ensure the strength of the defense supply chain? How can the United States strengthen its ecosystem of manufacturing expertise and production capacities in key sectors?

2. **Capitalizing on national investments in research and development (R&D):** What steps are needed to ensure that America captures the wealth generated from new products and processes emerging from its large national R&D spending? How can the United States achieve first-mover advantage in research-intensive advanced technology products?

3. **Ensuring financing for hardware start-ups and scale-ups:** What policies and programs would increase opportunities for manufacturing start-ups to thrive, scale their operations, and root production in this country?

These questions are at the heart of the grand challenges facing U.S. manufacturing. Roundtable participants were asked to identify actionable recommendations for both public and private stakeholders that would meet these challenges. Their assessment of the urgency of the challenges and recommendations are presented in this report. Because so much information was gathered about multiple industries, research programs, and competing national strategies, this report is the first of several on grand challenges forthcoming from MForesight.

Advances in production technology are changing manufacturing, presenting an opportunity for dramatic change that can restore national production for both defense and economic security. But, as more than 100 roundtable participants agreed, another report will not restore U.S. manufacturing competitiveness. Bold initiatives, with full understanding of the multi-faceted nature of the challenges, are necessary. The recommendations in this report include such bold steps.

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EXECUTIVE SUMMARY

American manufacturing faces both daunting challenges and transformative opportunities. As production has moved offshore over recent decades, manufacturers have steadily moved research and development (R&D) activities offshore as well to be close to the factories where product and process engineering skills reside. These shifts have come with serious consequences. America has seen a decline in its ability to manufacture new advanced technology products. Rebuilding capacity in advanced industries is essential to achieving long-term prosperity, ensuring national security, and preserving the nation's innovation edge. Doing so will require foresight, skillful cross-sector thinking, and serious investments.

New opportunities are also emerging: extensive, pervasive technological change in manufacturing should create a positive future for domestic production. The new parameters play to American strengths:

- flexibility and adaptability,
- a large capital market,
- superior higher education, and
- world-leading R&D.

But recapturing industrial leadership will require recognition of the importance of manufacturing and a focus on launching the industries of the future.

In early 2018, MForesight: Alliance for Manufacturing Foresight conducted a series of roundtables with manufacturing experts, business leaders, academic researchers, entrepreneurs, investors, and policymakers in cities across the United States. The objective was to gather perspective on the current state of U.S. manufacturing, the grand challenges facing U.S. manufacturing, and actions that the public and private sectors should take to meet those challenges. Their assessment of the urgency of the challenges and steps to meet them informed the critical next steps identified in this report.

Grand Challenges in U.S. Manufacturing

A simple articulation of the grand challenges that must be addressed to capture this prosperous future include:

1. Rebuild the Industrial Commons

The United States has lost fundamental production skills and capabilities—the Industrial Commons—in many industries.[1] This has meant the loss of entire industrial sectors over time, with noticeable impacts on the national innovation system. Production can provide competitive advantages that are difficult to replicate. Maintaining domestic manufacturing capabilities is essential to retaining the know-how needed to produce next generation technologies and to meet critical defense production.

1 Pisano, G. P., & Shih, W. C. (2009). Restoring American competitiveness. Harvard Business Review, (July - August). Retrieved from https://hbr.org/2009/07/restoring-american-competitiveness; Pisano, G. P., & Shih, W. C. (2012). *Producing prosperity: Why America needs a manufacturing renaissance*. Boston, Mass.: Harvard Business Review Press.

2. Convert national R&D to national wealth and security

Leading the world in R&D spending is not sufficient to ensure prosperity. **Technologies invented here are being licensed, sold, or given away to manufacture overseas, which, in effect, is subsidizing R&D for other countries.** Results of R&D should be strategically nurtured to create new products, including defense-critical technology products, that are made in America at commercial scale to generate wealth, jobs, and exports.

3. Lead emerging industries

To ensure future economic strength and defense superiority, the United States must have a leadership position in emerging industries such as autonomous vehicles, robotics, multi-material additive manufacturing, bio-manufacturing, energy storage, advanced materials, and quantum computing, to name a few. Dependence on foreign suppliers is creating defense vulnerabilities and significant long-term costs.

Bold steps are needed to ensure that these challenges are met quickly and aggressively. Market forces alone are unlikely to achieve the needed change. They have not so far. With sustained, strategic investments, the United States can

- regain fundamental manufacturing capabilities,
- ensure a return on federal investments in R&D,
- capitalize on technology changes broadly affecting manufacturing,
- establish leadership in new industries, and
- restore the broad-based supplier networks that are essential to economic and national security.

Restoring U.S. manufacturing leadership and, perhaps more importantly, restoring the nation's ability to capture wealth from the national innovation system with a robust manufacturing base, is a challenge to both the private and public sectors. Manufacturers, driven by short-term financial incentives, primarily focus on applied research and incremental product development rather than the translational research needed to commercialize basic research results to capture the "next big thing." Only government can overcome this market failure to ensure that the United States remains globally competitive.

Critical Next Steps

Addressing these grand challenges in manufacturing will require concerted effort from the nation's public and private sectors. Critical next steps include:

1. Invest in translational research and manufacturing innovation

The innovation cycle that converts R&D results—new inventions and discoveries—into successful commercial products may be working well in software, but it is subject to significant failures with regard to manufactured hardware. Funding for the translational research needed to develop operational prototypes, demonstrate manufacturability, and identify viable markets is frequently unavailable. Promising technologies languish in laboratories. Funding and expertise is needed to fill this gap. Effective investment can result in more prototyped and demonstrated products, reducing technical and market risks and boosting commercialization and production.

2. **Encourage pilot production and scale-up**
   To restore domestic production and overall leadership in emerging industries, America needs to invest in advancing manufacturing technologies, increasing pilot production, and scaling up to viable commercial volume. In some cases—semiconductor packaging and pharmaceuticals are examples—new production technologies are creating opportunities for U.S. industry to regain leadership. In others, commercial scale production can be achieved by ensuring patient capital is available and demand is sufficient. Leveraging government procurement is an effective tool.

3. **Empower small and medium-sized manufacturers**
   While these manufacturers form the backbone of industrial supply chains, they tend to implement new technologies slowly. There is a pressing need for mechanisms to accelerate the use of smart manufacturing technologies, increase their access to necessary expertise, and build better links between market demands for production capability and their ability to provide it. Mechanisms are also needed to increase small firms' capacity to commercialize research results, such as simple licensing agreements that will encourage technology transfer from universities.

4. **Grow domestic engineering and technical talent**
   To rebuild the Industrial Commons, a combination of incentives could increase the number of manufacturing apprenticeship programs, train engineering technicians with applied engineering skills, and entice capable domestic graduates to pursue advanced degrees to overcome America's dependence on foreign graduate students in key scientific and engineering fields.

The United States needs a broad national conversation to identify the necessary steps to achieve these objectives. At MForesight's roundtables, diverse stakeholders presented a number of promising ideas, including establishing a "focal point" office in the federal government for leveraging the strengths and outcomes of different agencies to mature Technology Readiness Levels (TRLs) and manufacturing research to mature Manufacturing Readiness Levels (MRLs) so that emerging technologies can be manufactured domestically at commercial scale. Other ideas included establishing university-affiliated Translational Research Centers, launching special competitions focused on manufacturing challenges, creating industry fellowships to harness the expertise of retired manufacturing experts, and building the financial resources to increase investment in hardware start-ups and scale-ups, among other ideas.

Implementation Options

These ideas should be part of a comprehensive national strategy, ideally implemented in a coordinated way with a single point of focus to orchestrate the required funding streams and to maintain strategic program management. The roundtable participants proposed a few implementation options, including creating a national innovation initiative, establishing a national manufacturing innovation foundation, and establishing a manufacturing program within each of the federal science and technology agencies. They fully expect the policymakers to convene and make decisions on how best to implement the critical steps identified in the previous section. A piecemeal approach, addressing one or two critical steps but not all, will not help.

Conclusions

1. Manufacturing *really* matters for economic and national security.
2. Being the best in the world in scientific discoveries and engineering inventions is critical but not sufficient to ensure national prosperity.
3. Manufacturing and innovation are intricately linked. Reaping the full rewards of rapid technological advances, the nation must manufacture today's advanced technology products so it can innovate next generation products.

Because of a confluence of economic and technological forces, the United States now has an opportunity to rebuild its manufacturing base and restore its global competitiveness. But another report will not help. Bold steps commensurate with the scale and importance of the objectives are absolutely necessary. **Other countries are not standing still. The onus is on us.**

INTRODUCTION

"If any particular manufacture was necessary, indeed, for the defense of the society it might not always be prudent to depend upon our neighbors for the supply."
Adam Smith, *An Inquiry into the Nature and Causes of the Wealth of Nations,* 1776

Advanced technology manufacturing industries in the United States are in a precarious position. After decades of shifting production offshore to reduce labor costs, fundamental production skills and capabilities have been lost; domestic suppliers of essential parts and components are unavailable; and the ability to manufacture new advanced technology products is severely constrained. As production has moved offshore, manufacturers are moving more research and development (R&D) to be close to the factories where the product and process engineering skills reside. The implications for future technology leadership, economic growth, and national security are dire. **Maintaining the trajectory of recent decades—a shrinking manufacturing base and large trade deficits in advanced technologies—will result in a second tier industrial economy, unable to maintain superiority in defense or global economic leadership.** Signs of this ominous future are already apparent.

Fortunately, the possibility of a competitive, prosperous future is also apparent. Extensive and pervasive technological change in manufacturing is creating an opportunity to ensure a positive future for domestic production. The coming decades promise a much more responsive, flexible, and intelligent manufacturing sector. Small batch, customized, local production will be both feasible and necessary to meet evolving consumer demand. These advanced manufacturing technologies are shifting the basis for competitive production in many industries, away from low-cost labor inputs toward effective use of smart, digital, flexible production. This manufacturing revolution is shifting priorities for skill development, capital investment, production location, product features, and multiple other parameters that were once common wisdom. **The new parameters play to American strengths: flexibility and adaptability, a large capital market, superior higher education,**

and the world's best R&D. In fact, Deloitte projects that the United States will top its Global Manufacturing Competitiveness Index in 2020, ahead of China, largely based on implementation of advanced manufacturing technologies and a shift to higher value, more sophisticated products.[2] But taking advantage of these strengths to recapture industrial leadership will require national recognition of the importance of manufacturing and a focus on building the industries of the future.

Grand Challenges in U.S. Manufacturing

Despite the federal government investing over $140 billion in R&D year after year, annual U.S. trade deficits in advanced technology products continue to hover around $100 billion. Federal science and technology (S&T) agencies and American universities and national laboratories funded by them continue to be successful in developing promising scientific discoveries and inventions. However, in too many cases, foreign governments and investors have been taking advantage of promising results, building large production capacity, and exporting the products back here. Consumer electronics, personal computers and laptops, lithium-ion batteries, flat panel displays, photovoltaics, nanotechnology, and biomanufacturing are all examples. American taxpayers have funded the basic research, only to create wealth and jobs elsewhere. Fixing this gaping hole in the nation's innovation ecosystem requires that the United States make the investments being made by competing countries—investment in engineering and manufacturing processes and equipment. Science is not engineering. Distinct from science, engineering means not just analysis and discovery but synthesis and innovation aimed at turning promising, albeit abstract, ideas into tangible new products and processes. Committing additional investment funds to translate promising discoveries and inventions into commercial products will be an essential step in restoring U.S. leadership (and the trade balance) in advanced technologies.

The longer the status quo continues, the more difficult and expensive solutions will become. Understanding the extent of the problem should motivate action now. A simple articulation of the grand challenges that must be addressed to capture a prosperous future include:

Rebuilding the Industrial Commons: The United States has lost fundamental production skill and capabilities—the Industrial Commons—in many industries and has lost entire industrial sectors, with noticeable impacts on the national innovation system. Gary Pisano and Willy Shih, professors at Harvard, identified the importance of the Industrial Commons and raised an alarm about its loss in 2009(!).[3] Many of the industries they identified as "at risk" then, such as electronic displays and mobile handsets, have already been lost.

Gaining competitive advantage from manufacturing: Production can provide competitive advantages that are difficult to copy and have long-term sustainability. There is a difference between parts and assemblies that become commodities as technology advances and manufacturing *capabilities* that become devalued as a source of competitive advantage

2 Deloitte & U.S. Council on Competitiveness. (2016). *2016 global manufacturing competitiveness index*. Deloitte Touche Tohmatsu Limited. Retrieved from https://www2.deloitte.com/global/en/pages/manufacturing/articles/global-manufacturing-competitiveness-index.html

3 Pisano, G. P., & Shih, W. C. (2009). Restoring American competitiveness. *Harvard Business Review*, (July - August). Retrieved from https://hbr.org/2009/07/restoring-american-competitiveness; Pisano, G. P., & Shih, W. C. (2012). *Producing prosperity: Why America needs a manufacturing renaissance*. Boston, Mass.: Harvard Business Review Press.

because Asian manufacturers, backed by mercantilist government policies, offer to produce for little or no margins. Maintaining domestic manufacturing capabilities is essential to retaining the know-how needed to produce next-generation technologies, and to retaining critical defense production.

Converting U.S. R&D to national wealth and security: Leading the world in R&D spending does not ensure prosperity or national security. The nature of research is such that a relatively small percentage results in the potential for new products, processes, even entire industries. These promising results must be nurtured to commercialize them in this country to generate wealth, jobs, and exports. Too often, once a discovery is proven in the laboratory, funding dries up. New inventions either languish for lack of funding to develop proof-of-concept prototypes; cannot be manufactured domestically for lack of capital, skills, or production capabilities; or are made in China. Technologies invented here are being licensed, sold, or given away to manufacture overseas, which, in effect, is doing R&D for other countries. The United States needs both a national strategy and effective mechanisms to build wealth through manufacturing promising research results rather than allow foreign entities to cherry-pick winners.

Capturing the gains from new manufacturing technologies: Advances in technologies ranging from high-performance materials to ubiquitous sensors, from self-correcting robots/machines to autonomous factories, will transform both products and processes. Maximizing the benefits will require rapid, broad implementation, which in turn will require that the necessary equipment and tools, talent and skills are available especially to small and medium-sized manufacturers (SMMs). Adoption of "smart manufacturing" technologies has been too slow to date. Resources, incentives, and support must be mobilized to move quickly, learn from mistakes, and sustain successes across all tiers and industries.

Leading emerging industries: To ensure future economic strength and defense superiority, the United States must have a leadership position in emerging industries such as autonomous vehicles, robotics, metal-additive manufacturing, biomanufacturing, energy storage, advanced materials, and quantum computing, to name a few. Dependence on foreign suppliers, regardless of how much cheaper they may be, is creating defense vulnerabilities and long-term competitive disadvantages. Labor cost differentials across countries are shrinking and direct labor is rarely a significant share of total production costs in advanced industries. There is little excuse not to lead in emerging industries and to maintain a strong competitive position.

Bold steps are needed to ensure that these challenges are met quickly and aggressively. Market forces alone will not achieve the needed change. In fact, market failures have made the problems worse over time. **With sustained, strategic investments, the United States can regain fundamental manufacturing capabilities, ensure a return on federal investments in R&D, capitalize on technology changes broadly affecting manufacturing, establish leadership in new industries, and restore the broad-based supplier networks that are essential to economic and national security.**

LOSING THE INDUSTRIAL COMMONS

The Industrial Commons is the set of knowledge and practical skills, supply chains and production capacity, materials and equipment, and overall industrial ecosystems that enable manufacturing across multiple industries. The term was coined by Pisano and Shih in 2009 and further elaborated in 2012.[4] Even before then, many studies, some dating back to the 1980s, have lamented the loss of U.S. manufacturing competitiveness. Despite remarkable advances in technology and a few government programs intended to strengthen domestic manufacturing, the situation has grown progressively worse over decades. Restoring the Industrial Commons is essential to restoring U.S. manufacturing competitiveness, but the more time passes, the more complex and expensive solutions have become.

Current State of U.S. Manufacturing

A few indicators of the current state of U.S. manufacturing are instructive. First consider the U.S. trade balance in advanced industries. As Figure 1 illustrates, in 2016 the United States had a positive trade balance in only two advanced industries: aerospace and (barely) engines and turbines.[5] Even in industries such as medical devices and pharmaceuticals, in which the federal government invests significant R&D and is the single largest customer, the nation does not maintain a positive trade balance. Furthermore, most *domestic* manufacturing industries use substantially more imported content than they did 20 years ago, as illustrated in Figure 2.[6] Imported content

4 Ibid.
5 IBISWorld. (2017). [Relevant industry reports]. Retrieved from IBISWorld database.
6 McKinsey Global Institute. (2017). *Making it in America: Revitalizing US manufacturing.* McKinsey & Company. Retrieved from https://www.mckinsey.com/featured-insights/americas/making-it-in-america-revitalizing-us-manufacturing

FIGURE 1: Net U.S. Exports in Advanced Industries ($ Billions)

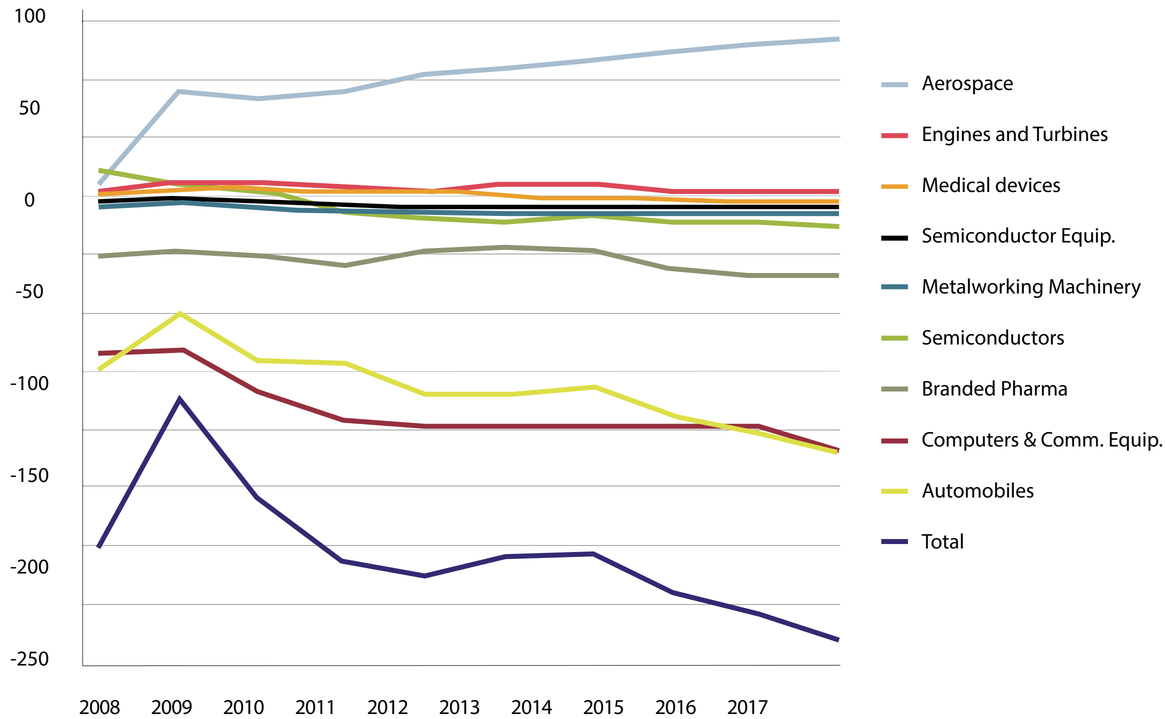
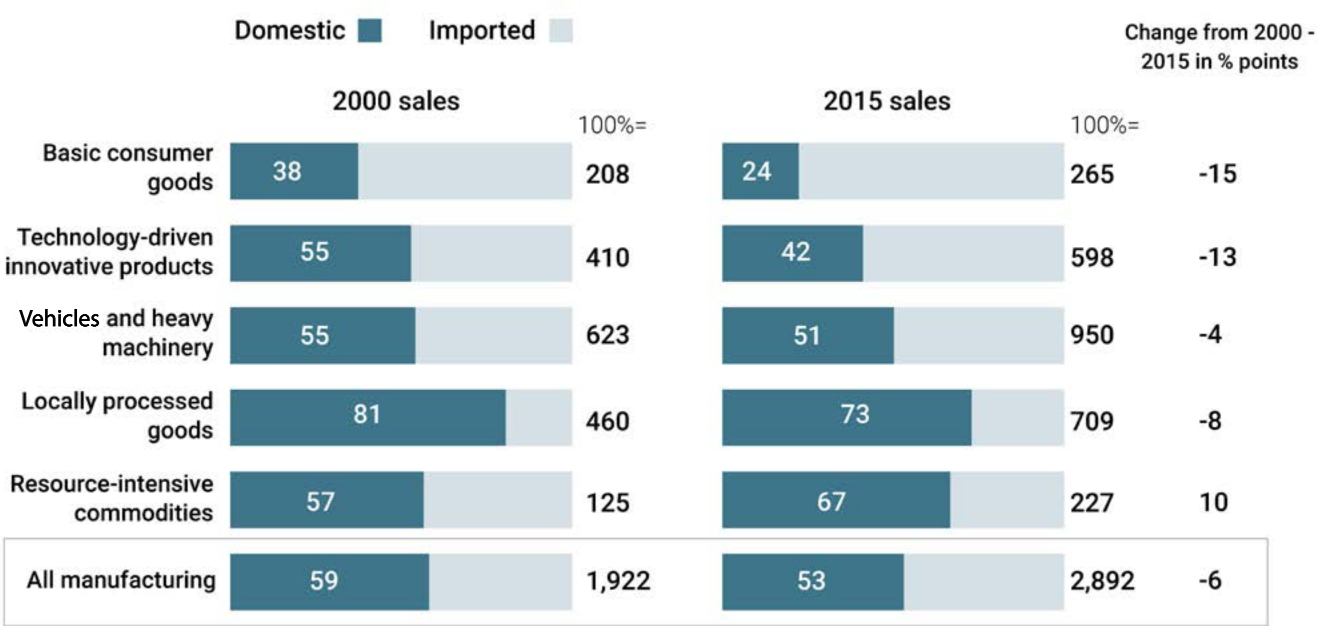


FIGURE 2: Change in Imported Content in U.S. Manufacturing (%,$ Billion)

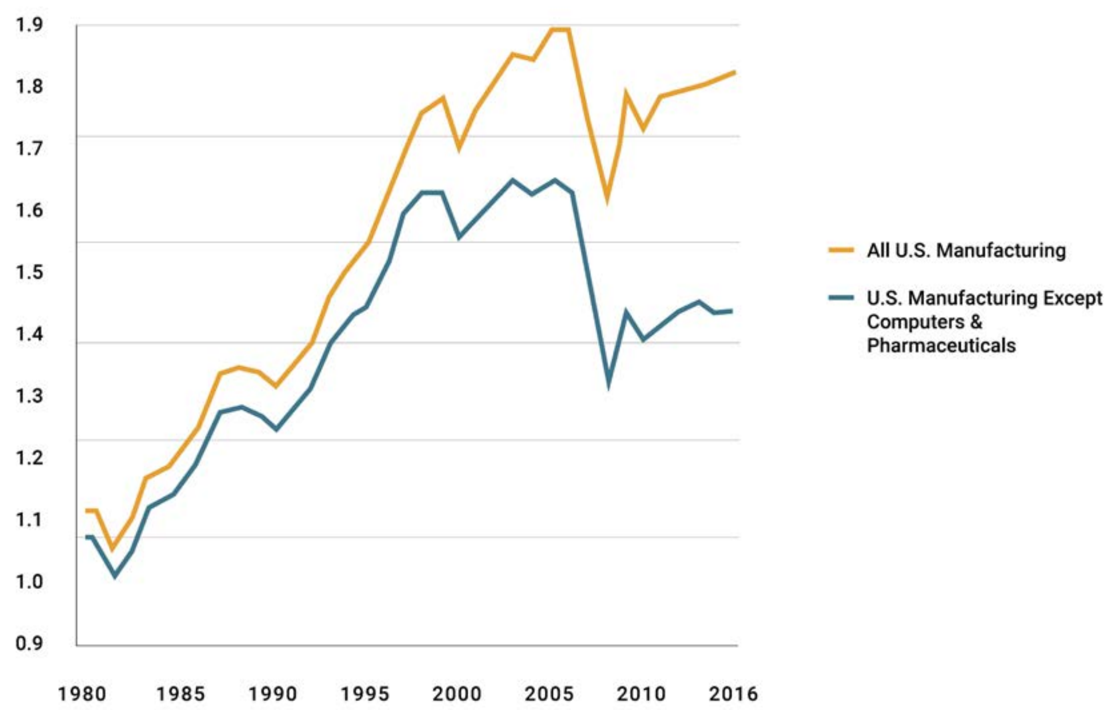


in technology-driven innovative products has grown from 45 to 58 percent in the past 15 years with no sign that the trend will change. One direct result from the growth of imports is that real value added in U.S. manufacturing is hardly higher now than in the mid-1990s (Figure 3); excluding computers and pharmaceuticals, it is barely 40 percent higher than in 1980, over 35 years in which U.S. gross domestic product (GDP) grew more than 2.5 times.[7] The United States has already fallen behind Japan, South Korea, Germany, and other European nations in manufacturing value added as a percentage of GDP and in the value added contributed by high-technology industries to total manufacturing value added.[8]

These statistics lend credence to what has become accepted wisdom—the United States is a post-industrial economy, fully globalized and integrated into the international production system. For many, manufacturing has simply followed the same path as agriculture, becoming a smaller proportion of GDP and providing fewer jobs, while national specialization moves to higher value activities. But manufacturing, especially but not exclusively, high-technology product manufacturing, is essential to national security. Manufacturing at scale is intricately linked to the ability to innovate next-generation products, yet domestic manufacturing is not the national priority it should be.

On one hand, it has become common wisdom that "manufacturing is done in China." Kai-Fu Lee, a former senior Google executive, who now runs a venture capital fund and accelerator

FIGURE 3: Change in Manufacturing Value Added



7 Ibid.
8 Biting the bullet: China sets its sights on dominating sunrise industries. (2017). *The Economist.* Retrieved from https://www-economist-com.proxy.lib.umich.edu/news/finance-and-economics/21729442-its-record-industrial-policy-successes-patchy-china-sets-its-sights

in Beijing, put it this way: "Innovation moves faster here."[9] On the other, it is increasingly clear that globalization, mostly driven by U.S. manufacturers moving production to low-wage countries in Asia, has had significant detrimental effects on the U.S economy. **The loss of Industrial Commons means that not only are an increasing number of advanced technologies manufactured abroad but also that the United States *cannot* manufacture many of them.** Skills have been lost, supply chains nearly eliminated.

Moving Production Offshore

Much of the initial offshoring stampede was led by consumer electronics in the 1960s after the invention of transistors, widespread use of standard shipping containers, and low-cost assembly workers in Asia lowered the cost and expanded the market for consumer radios and televisions. Offshoring accelerated significantly after China joined the World Trade Organization in 2001 and as the capabilities of Asian producers increased, leading to U.S. firms contracting design and, ultimately, product development. By abdicating production, U.S. firms lost the ability to innovate and, in many cases became nothing more than brand names—think Sylvania, Magnavox. By the new millennia, virtually all consumer electronics were designed and made in Asia, along with personal computers and laptops. As would be expected, production of almost all the components shifted to Asia, too, despite serious concern by both industry and government in the late 1980s and early 1990s over the urgency of maintaining domestic production in areas such as dynamic random access memory (DRAM).

By the time new consumer electronic devices emerged, such as the iPod and later smart phones, domestic manufacturing was impossible because all the components were manufactured in Asia, despite the research to create these components in the first place all done here (see Figure 4). Research funded by the Department of Defense (DoD), the National Science Foundation (NSF), the National Institutes of Health (NIH), the Department of Energy (DoE), and the National Institute of Standards and Technology (NIST) contributed to the breakthrough technologies of magnetic storage drives, lithium-ion batteries, and the liquid crystal display, which came together in the development of MP3 devices and later in iPods and iPhones. The device itself is innovative, but it built upon a broad platform of component technologies, each derived from fundamental studies in physical science, mathematics, and engineering.[10]

The ramifications of this lost production base have become profound. For instance, the leading disruptive force in the global economy has been mobile communications. The United States invented cellular communication technology and in the early years, companies like Motorola manufactured phones in this country. Although Apple led the shift to smart phones beginning in 2007, no iPhones were ever manufactured here. By then, all the inputs to the iPhone—display, memory, communication chips, etc.—were manufactured in Asia. Even sophisticated application-specific integrated circuits (ASICs) were made in Asian, primarily Taiwanese, semiconductor foundries. Successive generations of iPhones have followed the same pattern, in many cases with Apple providing assistance to their Asian suppliers to ensure access to sufficient

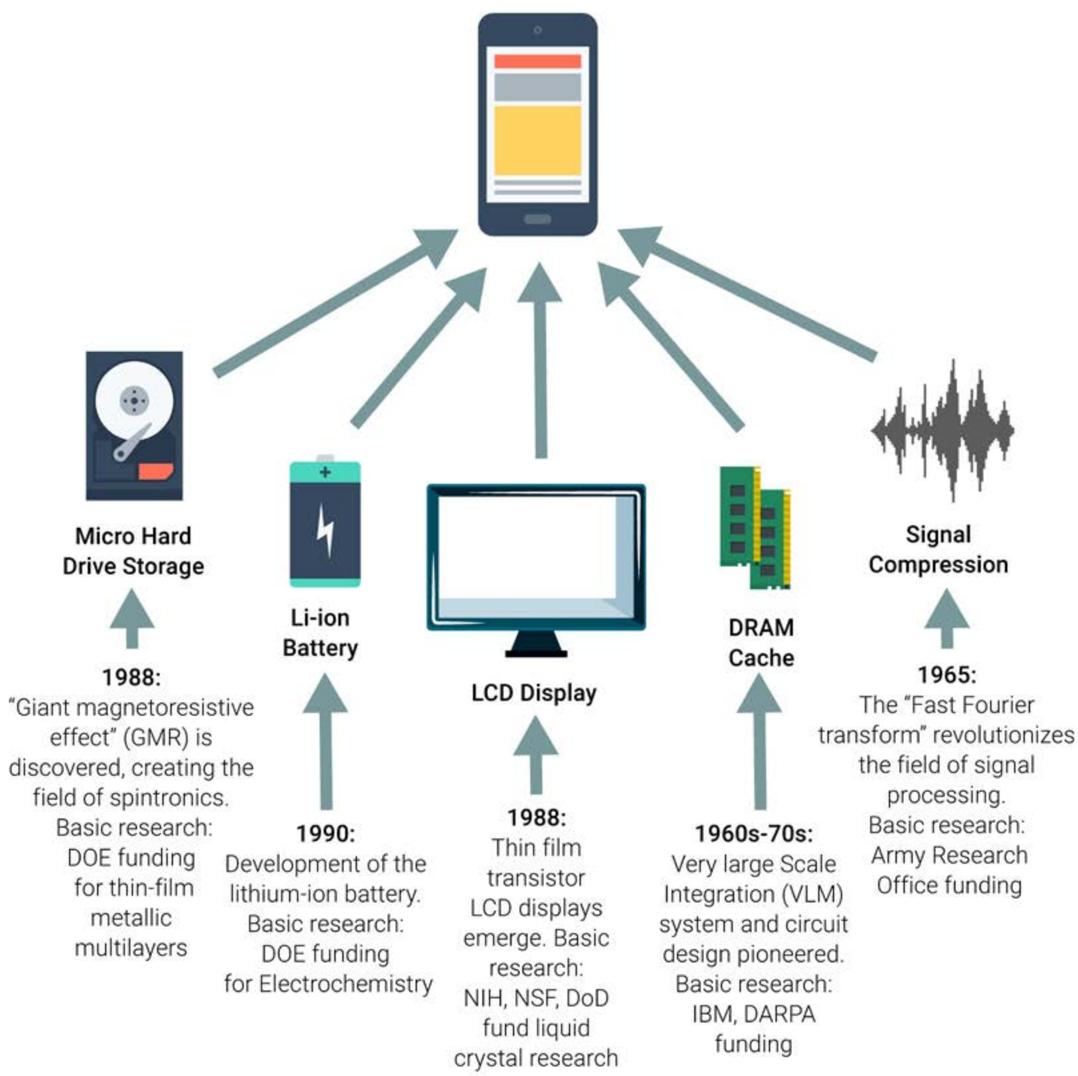
9 The next wave: China's audacious and inventive new generation of entrepreneurs. (2017). *The Economist.* Retrieved from https://www-economist-com.proxy.lib.umich.edu/briefing/2017/09/23/chinas-audacious-and-inventive-new-generation-of-entrepreneurs

10 Domestic Policy Council. (2006). *American competitiveness initiative: Leading the world in innovation*. Office of Science and Technology Policy. Retrieved from https://files.eric.ed.gov/fulltext/ED503266.pdf

production equipment and continue to raise their manufacturing capabilities. The results have been stellar for Apple profits, share price, and iPhone consumers, but the United States has no foothold in actually making the single most important product segment of the current era.[11] Even Android smartphones, some designed by Google and other American firms, are not, and cannot, be made in the United States.

Flat panel displays are another broad category of electronics that cannot be manufactured in this country despite their ubiquity. Again, the technologies that enable most flat panel displays were invented by U.S. companies and universities. Few, if any, factories for LCD and LED large diameter flat panel displays were ever opened in the United States.[12] **Without that production experience, U.S. companies have been unable to commercialize the**

FIGURE 4: Example of Domestic Research Results Moving Offshore



11 Half of all iPhones are assembled by Foxconn in Zhengzhou, China at a factory that employs 350,000 during peak production. Barboza, D. (2016, December 29). How China built 'iPhone city' with billions in perks for Apple's partner. *The New York Times*. Retrieved from https://www.nytimes.com/2016/12/29/technology/apple-iphone-china-foxconn.html
12 There are currently two U.S.-based producers of OLED micro displays, Kopin in Westborough, Massachusetts and eMagin in Bellevue, Washington.

next generation of flexible displays, despite significant R&D investments by the U.S. military.[13]

At least part of the explanation for the shift of semiconductor and electronic production to Asia is found in the early days of the semiconductor industry. At the outset, American companies such as Intel, AMD, Texas Instruments, and Motorola controlled the entire value chain, from design through manufacturing and packaging of semiconductors. Initially, packaging was a labor-intensive process. Microchips are packaged in plastic or ceramics with pins that fit into circuit boards. Wiring from the chip to the pins was a manual process, with workers using microscopes to attach the wire leads. Low-cost labor in Asia, initially Taiwan, Singapore, and Malaysia, was essential to limit overall production costs. Once packaging moved to Asia, the expertise in packaging technology moved near the factories, and the growth of Asian foundries made sense to be near the packaging experts. And once the total semiconductor value chain was mostly in Asia—Intel, GLOBALFOUNDRIES, Samsung, Micron Technologies, and NXP are among the exceptions with semiconductor fabrication facilities (fabs) in the United States—it made sense for major users of semiconductors such as consumer electronics and computers to locate factories in Asia, too.

The United States is no longer where companies build new fabs. In 2011, of 27 high-volume fabs built worldwide, only one was in this country; 18 were in China and 4 in Taiwan. In 2018, 20 new fab projects had been announced in China, with total investment exceeding $10 billion.[14] Meanwhile, the total number of fabs in the United States was projected to decline from 123 in 2007 to 95 by 2017. Predictably, as the industry has moved, the supply chain has gone with it. U.S. companies continue to have a majority of global market *sales* of semiconductors according to the Semiconductor Industry Association, but that share includes fabless companies, such as Nvidia and Qualcomm, that have designs manufactured in Asia by semiconductor foundries such as TSMC in Taiwan, the market leader.

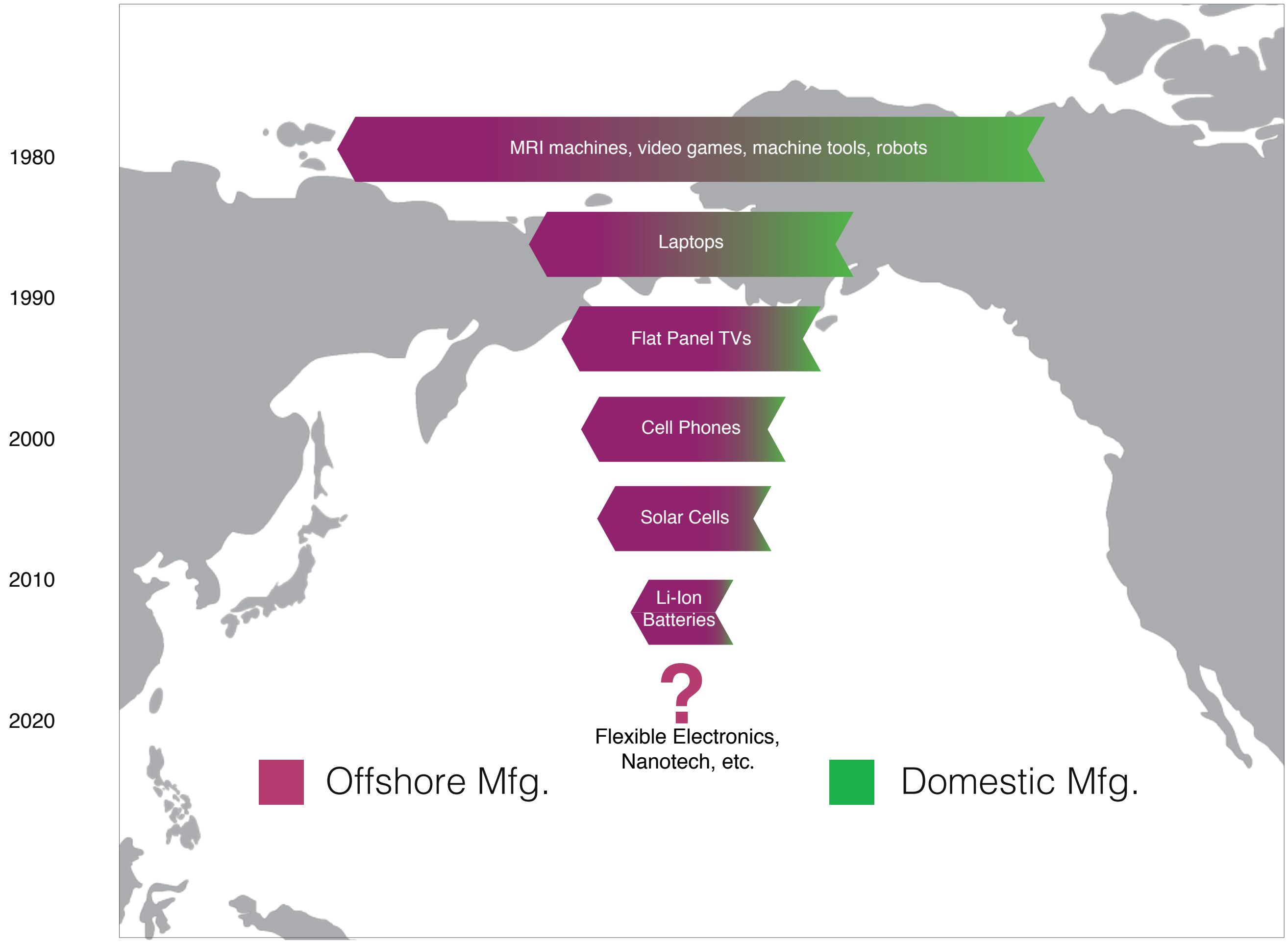
The American justification for relying on Asian electronics manufacturers is that these are high-cost, low-margin links in the value chain; U.S. firms capture the bulk of profits. While true at the moment, at least for some companies, this same logic began the offshoring of consumer electronics that led to the loss of the entire industry. If U.S. companies are dependent on foreign producers, ultimately their ability to innovate and meet rapid product cycles is likely to be infringed. In fact, in 2018, shortages of electronic components—multilayered ceramic chip capacitors, resistors, semiconductors, graphics cards—are growing as new markets and applications create surges in demand that mostly Asian manufacturers are unable to meet.[15] As data capture and processing becomes pervasive in both products and processes, the United States will face ever-increasing dependence on foreign manufacturers across even more economic sectors. Figure 5 illustrates how **this process of shifting production of new technologies offshore not only continues but has accelerated.** By not manufacturing high-technology products the nation loses the ability to innovate next-generation products, loses the

13 The Flexible Electronics and Display Center established by the U.S. Army at Arizona State University in 2004 includes multiple foreign partners such as Sharp, Auo, and LG.

14 Tseng, C., & Tracy, D. (2017). Fab investment surge in China. *SEMI*. Retrieved from http://www.semi.org/en/fab-investment-surge-china-0

15 McKeefry, H. L. (2018, April 20). Component shortages define first half of 2018…& beyond. *EBN*. Retrieved from https://www.ebnonline.com/author.asp?section_id=3219&doc_id=283376

FIGURE 5: Invent Here, Maufacture There - And Losing Faster
(Transition Time to Offshore Manufacturing)



opportunity to create manufacturing jobs and national wealth, and increases dependence on foreign sources for national security.

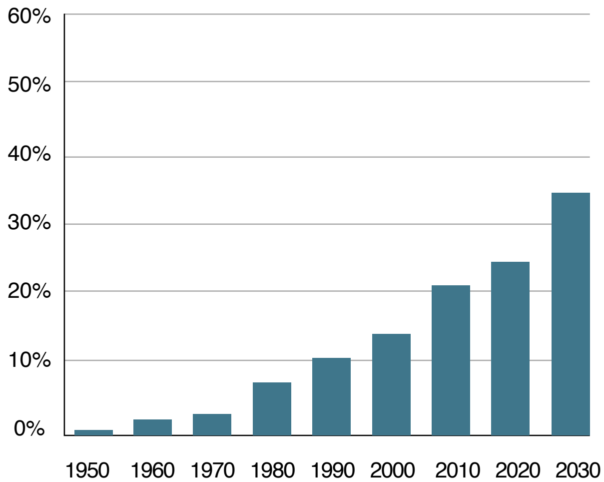
Potential Impacts on Emerging Industries

An obvious source of concern is automobiles. Electronics are projected to comprise half the value of automobiles in 2030, as the sensors and processors needed for autonomous vehicles (AVs) multiply (Figure 6).[16] Software development and R&D for AVs has clearly been a priority for automakers. Toyota, for example, has recently opened a research center in Silicon Valley and started software companies in Japan and the United States.[17] Ford has a Smart Mobility unit that has acquired start-ups in software and cloud computing, and has started a new “Ford X” incubator. Ford is also increasing spending on electric vehicles, with plans to launch 40 new battery and hybrid models by 2022. Several automakers have contracted with Nvidia (fabless), historically

16 Statista. (2013). Automotive electronics cost as a percentage of total car cost worldwide from 1950 to 2030. *Statista*. Retrieved from https://www.statista.com/statistics/277931/automotive-electronics-cost-as-a-share-of-total-car-cost-worldwide/

17 Buckland, K., & Sano, N. (2018, February 5). Toyota’s way changed the world’s factories. now the retool. *Automotive News Canada*. Retrieved from http://canada.autonews.com/article/20180205/CANADA01/302059902/toyotas-way-changed-the-worlds-factories.-now-the-retool

FIGURE 6: Automotive Electronics Percentage of Total Vehicle Cost



a leader in graphics processing units, for the processors needed for vehicle autonomy. Based on existing production capacity, the bulk of these electronic devices may be designed and engineered in this country, but most will be made in Asia. An exception is lidar supplier Velodyne, which opened a new factory in California in 2017 to manufacture its flagship lidar sensors.[18] Velodyne entered the lidar business in 2005 after participating in an autonomous vehicle competition by the Defense Advanced Research Projects Agency (DARPA). Its sensors are used in U.S. military vehicles.[19]

The emergence of AVs and the shift to electric drivetrains will have additional impacts on U.S. manufacturing where the transportation sector comprises 15-20 percent of manufacturing employment. For instance, under the current North American Free Trade Agreement (NAFTA) 62.5 percent of the net cost of a vehicle must originate in North America. Current U.S. proposals call for 75 percent of electric or AV value be manufactured in North America within nine years. Experts are skeptical that nine years will be sufficient to build sufficient electronics production capacity to meet that mandate.[20]

A shift to electric vehicles may further complicate domestic content objectives. According to some estimates, electric drivetrains, including batteries, require 40 percent less manufacturing labor than mechanical drivetrains that require internal combustion engines, transmissions, exhausts, and cooling systems.[21] Different skills will be needed, while at the same time, production is likely to be consolidated into fewer factories. Without growth in domestic production of batteries, motors, magnets, electrical harnesses, and other electric vehicle components, imports will magnify the adverse impact on the domestic industry.

Production of all of these components and systems has grown rapidly in China because of the demand created by the government mandate to have 20 percent of vehicles sold by 2025 to use alternative fuel. Historically, the United States has used defense procurement to accelerate industrial development. Examples include aircraft, computers, semiconductors, robotics, and information networks. Leveraging defense procurement in emerging industries would promote early adoption, support pilot production, and help to re-establish the Industrial Commons needed for subsequent commercial-scale manufacturing.

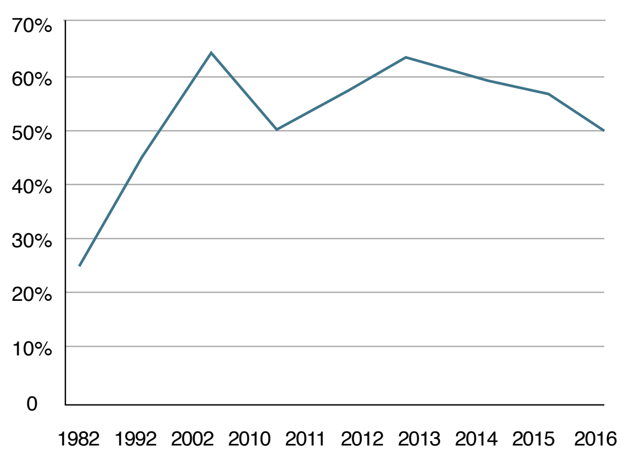
None of these issues in semiconductors and electronics are new, having reached the highest

18 Krok, A. (2018, January 2). Velodyne just made self-driving cars a bit less expensive. *Roadshow.* Retrieved from https://www.cnet.com/roadshow/news/velodyne-just-made-self-driving-cars-a-bit-less-expensive-hopefully/
19 Mozur, P., & Perlez, J. (2017, April 7). China tech investment flying under the radar, Pentagon warns. *The New York Times.* Retrieved from https://www.nytimes.com/2017/04/07/business/china-defense-start-ups-pentagon-technology.html
20 Carey, N. (2018, May 14). NAFTA math many not add up to more U.S. auto jobs. *Reuters.* Retrieved from https://www.reuters.com/article/us-trade-nafta-autos/nafta-math-may-not-add-up-to-more-u-s-auto-jobs-idUSKCN1IF0CP
21 Frost, L., & Taylor, E. (2017, September 11). Carmakers face electric reality as combustion engine outlook dims. *Reuters.* Retrieved from https://www.reuters.com/article/us-autoshow-frankfurt-electrics/carmakers-face-electric-reality-as-combustion-engine-outlook-dims-idUSKCN1BN00X

levels of government in the past. For instance, in 2005 the Defense Science Board (DSB) Task Force on High Performance Microchip Supply[22] outlined the potential consequences of "a profound restructuring" of the electronics industry caused by offshore outsourcing, the rise of increasingly competitive government-subsidized foreign producers, and substantial declines in federal support for basic R&D. The Department of Defense (D0D) did not adopt DSB's recommendations. In 2012, the Senate Armed Services Committee released the results of its investigation into electronic parts intended for weapons systems. **It found 1,800 cases of suspected counterfeit parts involving more than 1 million parts for use in the most important military systems; 84,000 suspect counterfeit electronic parts were supplied by one Chinese company.**[23] Additional concern was addressed by the General Accountability Office (GAO) in 2015 in their review of trusted defense microelectronics. GAO found that access to leading-edge microelectronics faced challenges due to supply chain globalization, production costs, and market trends, and that future access and capabilities are uncertain.[24] Finally, a January 2017 report by the President's Council of Advisers on Science and Technology[25] emphasized the importance of a robust domestic semiconductor industry for both national security and overall national innovation. It also identified the threat posed by aggressive Chinese industrial policies in this industry and the need, therefore, for the U.S. industry to maintain its lead through R&D and continued innovation. Oddly, although the report noted that the share of global fabrication capacity in the United States fell to about 13 percent in 2015, compared to 30 percent in 1990, it did not recommend any steps to encourage locating new fabs here. Even the best design and engineering of microchips is at risk without assured access to manufacturing. A few more reports are not going to turn the tide.

U.S. manufacturing issues created by the loss of Industrial Commons are not limited to electronics. **Foundational manufacturing capabilities have been significantly reduced or lost entirely as production in multiple industries has moved abroad.** Another prime example is machine tools and other production equipment. The United States once had a large, diverse machine tool industry with thriving clusters in Cincinnati and elsewhere. Foreign competition intensified in the 1980s as producers from Germany, Japan, and S. Korea built U.S. market share. In 1982 imports were only 26 percent of domestic consumption, but reached 64 percent in 2002 and 63 percent in 2012 (Figure 7). Currently, only one U.S.-owned

FIGURE 7: Import Penetration in the U.S. Machine Tool Market



22 Defense Science Board. (2005). *High performance microchip supply.* Office of the Under Secretary of Defense For Acquisition, Technology, and Logistics. Retrieved from https://www.acq.osd.mil/dsb/reports/2000s/ADA435563.pdf
23 Senate Armed Services Committee. (2012). Senate Armed Services Committee Releases Report on Counterfeit Electronic Parts. Retrieved from https://www.armed-services.senate.gov/press-releases/senate-armed-services-committee-releases-report-on-counterfeit-electronic-parts
24 U.S. Government Accountability Office. (2015). Trusted Defense Microelectronics: Future Access and Capabilities Are Uncertain. Retrieved from https://www.gao.gov/products/GAO-16-185T
25 President's Council of Advisors on Science and Technology. (2017). *Ensuring Long-Term U.S. Leadership in Semiconductors.* Executive Office of the President. Retrieved from https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/PCAST/pcast_ensuring_long-term_us_leadership_in_semiconductors.pdf

machine tool company, Haas, is among the top 15 in revenue. A combination of foreign companies building U.S. factories and changes in technology have reduced the import share to roughly 50 percent in recent years, but the manufacturing knowledge base embodied in the industry has yet to recover.[26]

Another foundational manufacturing capability is tool and die making. In 2012, the Congressional Research Service stated that the U.S. tool and die industry is in a precarious state, largely due to offshoring. As major manufacturing industries have shifted production offshore, the tool and die industry endured a disproportionate loss of jobs and companies. Between 1998 and 2012 over a third of U.S. tool, die, and mold makers closed and employment halved. Even then, the average age of a skilled toolmaker was 52, presaging a skill shortage being felt today.[27] Metal additive manufacturing could have a significant impact in reversing the negative trends in the tool and die industry, a critical foundational capability that calls for a national strategy and significant investment.

Even industries in which the United States has had a global leadership position, such as medical devices and pharmaceuticals, are now dependent on Asian producers for many of their products. In pharmaceuticals, more than 80 percent of the active ingredients are imported, mostly from China and India. Generic drugs comprise more than 85 percent of the U.S. market, but only 10 percent are manufactured domestically.[28] Other medical supplies, including basics such as intravenous solutions, syringes, surgical masks, and respirators are imported and frequently in short supply.[29] In medical devices, China provides about 12 percent of total U.S imports, including orthopedics, defibrillators, pacemakers, and magnetic resonance imaging scanners.[30]

Despite multiple reports raising alarms for years, there is little evidence of improvement. The simple reason is profit maximization by the private sector and a lack of a comprehensive, long-term national strategy by the public sector. To a great extent, this lost Industrial Commons is a consequence of U.S. corporate strategy to maximize profits by inventing here and making there. Economic conditions and financial incentives made this an effective strategy, and the positive financial results have outweighed any doubts or concerns for long-term national security or economic health. U.S. government policy, reliant on the free market principles of comparative advantage, has largely been supportive of offshoring production, turning a blind eye to the negative impacts on defense production and the long-term detrimental effects on the nation's Industrial Commons. Now, the consequences of moving production capacity and know-how offshore has forced a new strategy among many U.S. manufacturers and an accepted norm among public officials: *invent there, manufacture there.* The negative and dangerous ramifications of this trend cannot be overstated.

26 Unpublished data from The Association for Manufacturing Technology, based on census data.
27 Canis, B. (2012). The tool and die industry: Contribution to U.S. manufacturing and federal policy considerations. Congressional Research Service. Retrieved from http://www.ntma.org/uploads/general/Tool-and-Die-Industry.pdf
28 Koons, C. (2018, April 11). Why we may lose generic drugs. *Bloomberg.* Retrieved from https://www.bloomberg.com/news/articles/2018-04-11/are-drug-prices-too-low
29 According to federal data, only 5 percent of the more than 230 million surgical masks and 30 percent of the more than 20 million respirators bought by American health care each year are made in the United States. McKenna, M. (2018). Medicine's long, thin supply chain. *Wired.* Retrieved from https://www.wired.com/story/medicines-long-thin-supply-chain/
30 Kaplan, S., & Thomas, K. (2018, April 6). Why Trump's tariffs could raise the cost of a hip replacement. *The New York Times.* Retrieved from https://www.nytimes.com/2018/04/06/health/trump-tariffs-china-devices-drugs.html

Short Time Horizons and Shareholder Value*

Despite warnings about loss of manufacturing competitiveness going back to the 1980s, U.S. manufacturing has continued to shrink as a share of GDP, has had worsening trade balance in advanced technologies, and has become more dependent on foreign sources for critical inputs. The overwhelming conclusion is that market forces, specifically financial market forces, drive the managers of U.S. manufacturers to make decisions that have proven to be harmful to national interests. **These same forces are not evident in other advanced nations, such as Germany and Japan, that have maintained strong manufacturing sectors.**

Public corporations in the United States are frequently criticized for focusing on quarterly profits and changes to their stock price. This focus is partially driven by rapid turnover in stock ownership: **the average time investors hold a stock fell from eight years in the 1960s to only four months by 2012.** Further, senior management compensation typically combines salary and stock options, helping to drive decisions that will benefit shareholders. Ostensibly intended to maximize the value of the business for the owners of the business, using stock price as a proxy for business value drives short-term decisions. For manufacturers, over-emphasis on minimizing production costs results in offshoring of production and constant pressure on suppliers to lower costs; treating research as an expense to be avoided rather than a long-term investment reduces R&D spending; and using retained earnings (and tax windfalls) for stock buybacks rather than productive investments compromises long-term competitiveness.

This focus on shareholder value, now considered a cornerstone of American capitalism, is a relatively recent phenomenon, driven by policy changes in the 1980s. First, prior to 1982 antitrust standards restricted mergers, but antitrust guidelines were relaxed so that a large market share of a combined entity would not guarantee that a merger would be blocked. Second, the U.S. Supreme Court ruled in 1982 that state laws against hostile takeovers were unconstitutional because they limited interstate commerce. This change led to a rapid increase in hostile takeovers, from one in 1980 to more than 100 between 1984 and 1988. Third, tax reform in 1981 encouraged defined contribution retirement plans—termed 401k plans after the section in the legislation—which greatly increased the number of people owning stock, mostly through mutual funds. In 1982, mutual funds had $135 billion in assets; by 2017, assets totaled nearly $19 trillion. Mutual funds are now the largest owners of corporate stock, sometimes holding more than 10 percent of individual companies.

These changes caused and, over time, reinforced shareholder value as the primary touchstone for managers of public corporations. Yet, according to Gallup, only 52 percent of Americans own stock. **Foreign firms and U.S. private firms do not face the same pressure to maximize stock prices, and by many accounts, are more willing to make long-term investments and to consider the interests of all stakeholders when making management decisions.** The prevalence of so-called stakeholder capitalism in Germany, for example, is a significant reason that the German manufacturing sector remains more than 20 percent of its GDP.

* More detail can be found in *The Vanishing Corporation* by Gerald Davis (2016) and *The Shareholder Value Myth: How Putting Shareholders First Harms Investors, Corporations and the Public* by Lynn Stout (2012).

INVENT THERE, MANUFACTURE THERE

"Large-scale innovation has become an engine for China's economic development."

Matt Tsie, GM Executive Vice President and GM China President, May 2017[31]

The weak state of the U.S. Industrial Commons has had detrimental impacts on the entire national innovation ecosystem. As more production of advanced technologies has moved abroad, more research and product development has moved with it due to the close ties between product and process technologies. Studies have shown that manufacturers are twice as productive at R&D when that work is collocated with a factory. Yet, U.S. manufacturers continue to outsource. Since 2000, more than 70,000 manufacturing plants have closed or moved offshore, threatening the nation's innovation ecosystem. The ramifications can be seen not only in shifts in R&D spending by manufacturers, but also in the ability of U.S. innovators to make new products. **Because the nation is dependent on its ability to innovate, cracks in the system bode ill for long-term national prosperity as high-technology manufacturing is increasingly offshored**.

R&D Spending by Manufacturers

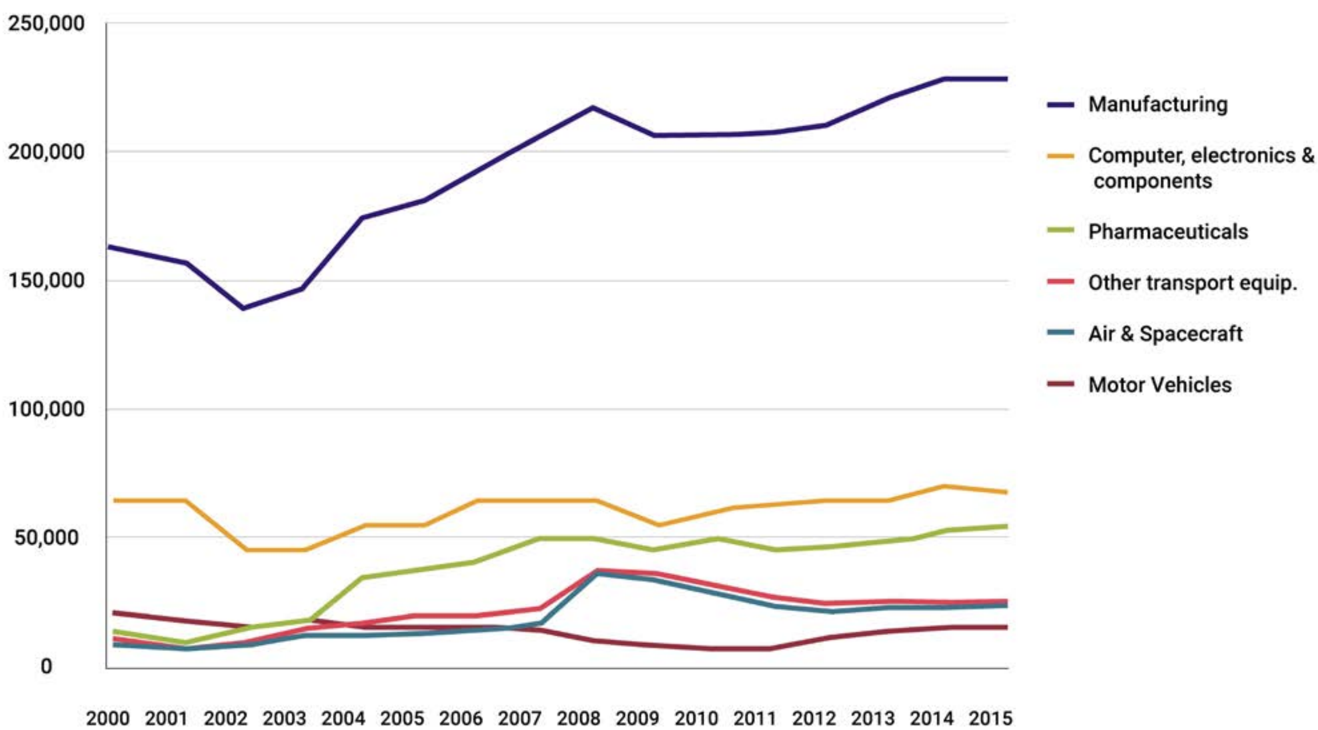
Recent years have witnessed a noticeable shift in R&D spending by U.S. manufacturers. Historically, manufacturing companies have been the largest corporate R&D spenders, driven by the need for new products, incorporating new technologies into existing products, and devising new, more efficient processes to make products. The share of R&D spending by manufacturers has been falling in

31 GM China science lab key to future global developments. (2017, May 23). *The Newswheel.* Retrieved from http://thenewswheel.com/gm-china-science-lab-key-to-future-global-developments/

the United States. In 1990 manufacturers spent more than 83 percent of total private sector R&D spending in the country; this fell to less than 60 percent in 2002 before recovering to 66 percent in 2015.[32] Most of the growth in recent years is attributable to the pharmaceutical industry, with other advanced manufacturing industries either declining or stagnating (Figure 8). **Perhaps more worrying, the focus of R&D spending, at least among publicly traded manufacturers, has steadily shifted toward development, especially incremental product development.** A 2007 study found that just 6 percent of companies published research in scientific journals, down nearly two-thirds since 1980. Largely due to pressure from investors, corporations spend less on basic science and have closed broad-based corporate research labs.[33]

A number of factors have changed this dynamic in the United States. First, as more production moves offshore, the locus of both product and process development moves with it. There are a few exceptions, such as Apple, that maintain control of product design and the processes used by suppliers to make those designs, but in many cases, the expertise gained by producing builds the expertise needed for new product design and development. A 2009 survey of U.S. semiconductor producers concluded that process R&D requires proximity to manufacturing operations.[34] In the aerospace industry, the trend toward increased outsourcing

FIGURE 8: U.S. R & D Spending in Advanced Manufacturing Industries (Millions Constant 2010 $)



32 ANBERD: business enterprise R&D broken down by industry. (2017). *OECD.Stat.* Retrieved from http://stats.oecd.org/Index.aspx?DataSetCode=ANBERD_REV4

33 Matthews, C. (2015, December 21). The death of American research and development. *Fortune.* Retrieved from http://fortune.com/2015/12/21/death-american-research-and-development/

34 Dewey & LeBoeuf. (2009). *Maintaining America's competitive edge: Government policies affecting semiconductor industry R&D and manufacturing activity.* Semiconductor Industry Association. Retrieved from https://www.semiconductors.org/document_library_and_resources/tax/maintaining_america_s_competitive_edge_government_policies_affecting_semiconductor_industry_r_d_and_manufacturing_ activities/

of parts and systems is seen as diminishing the long-term prospects for U.S. business jet manufacturers. **Industry representatives recognize that many of the best ideas for manufacturing innovation come from the factory floor.[35] Experience demonstrates in multiple industries that proximity to manufacturing fuels innovations in both products and processes.**

A recent survey of 369 manufacturers reveals the main benefits of moving R&D to China (Figure 9).[36] Most of the top reasons are directly related to the strength of China's Industrial Commons.[35] **U.S. companies have been most aggressive in moving R&D to China in the last decade.** Figure 10 illustrates both the growth in foreign companies' R&D spending in China and the predominance of U.S. companies compared to other major countries.[35] Over 40 percent of all foreign R&D investments in China are by U.S. corporations.

It is important to note that China has an explicit policy to attract foreign R&D centers with

FIGURE 10: Foreign R&D Spending in China

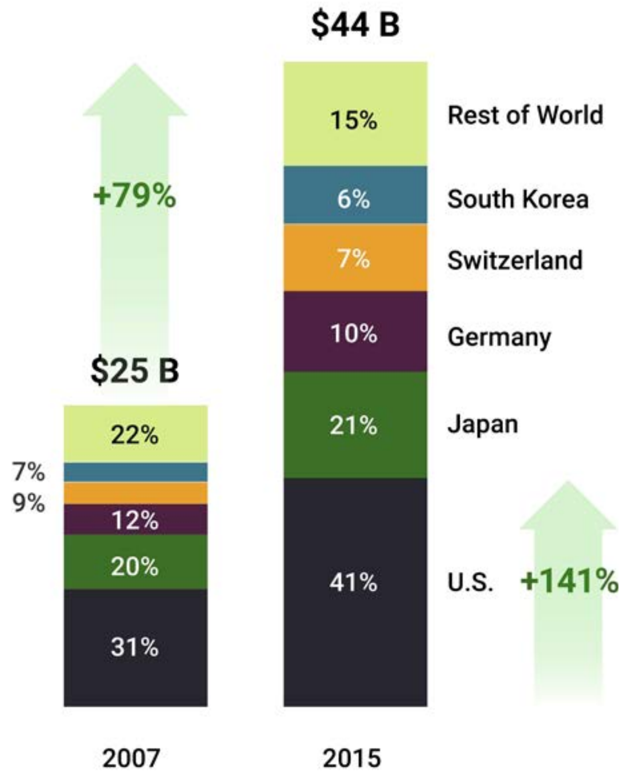
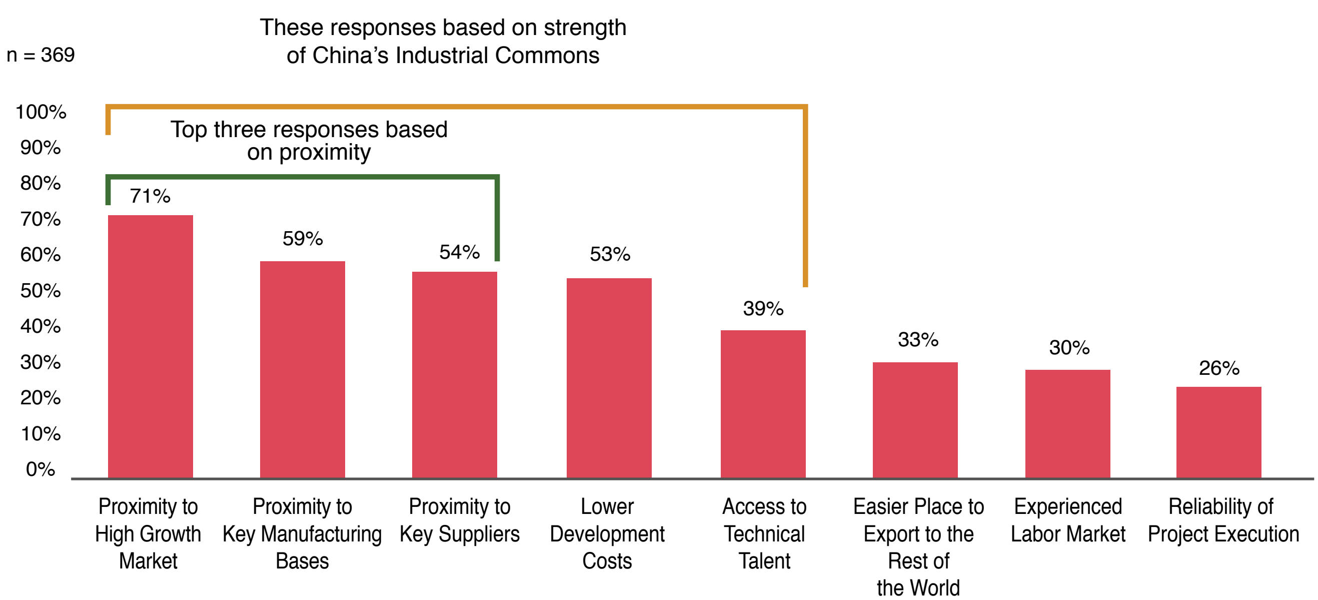


FIGURE 9: Factors driving manufacturing R&D to China



35 U.S. International Trade Commission. (2012). *Business jet aircraft industry: Structure and factors affecting competitiveness.* Retrieved from https://www.usitc.gov/publications/332/pub4314.pdf
36 Consultancy.UK. (2015, November 17). R&D and innovation spend increasingly moving to China. *Consultancy.UK.* Retrieved from https://www.consultancy.uk/news/2944/rd-and-innovation-spend-increasingly-moving-to-china

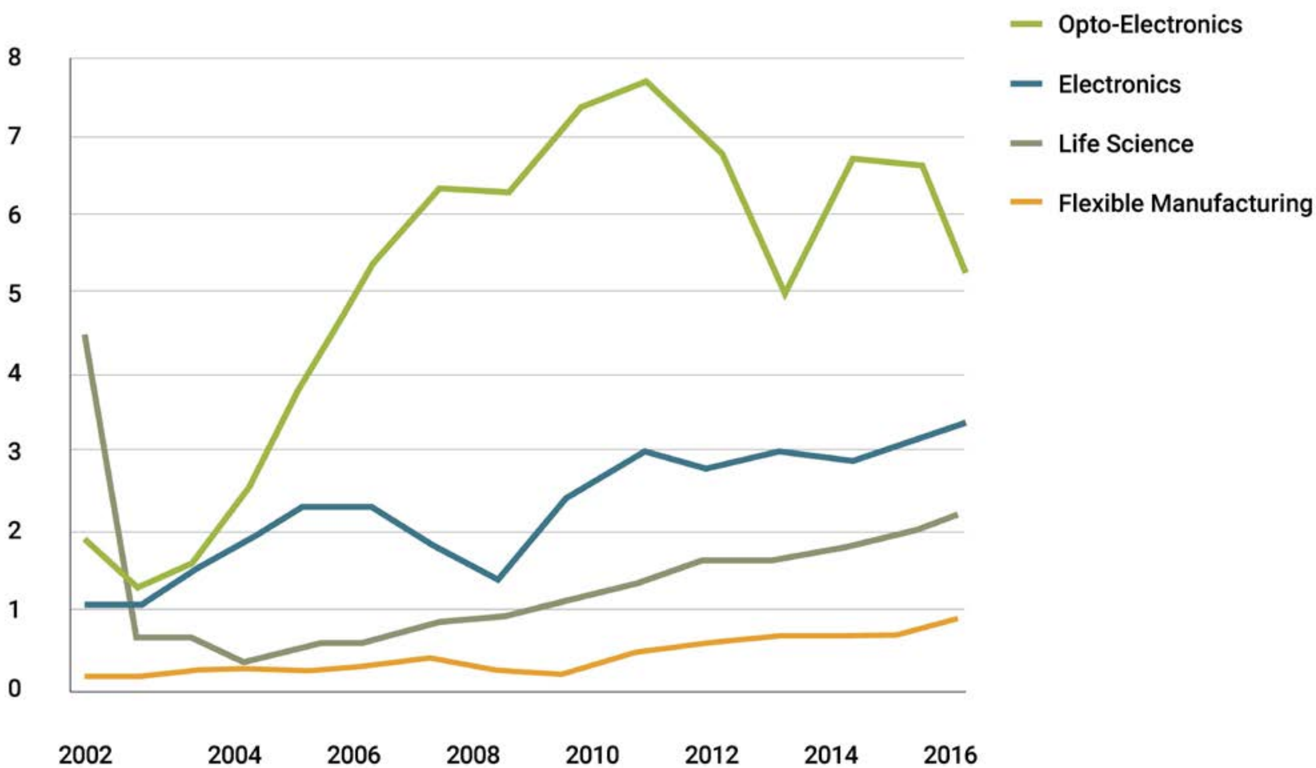
economic incentives and to recruit both expatriate Chinese and foreign scientists. The Thousand Talents program was launched in China in 2008 to attract academics to return to China. Using appeals to patriotism, financial incentives, and better career prospects, China has successfully attracted expatriate scientists with experience in defense research. So many scientists have been recruited back to China from Los Alamos National Laboratory that they have a moniker, "the Los Alamos club."[37]

A second factor reducing R&D investment by U.S. manufacturers is the growth of Chinese imports in advanced technology industries (Figure 11). Research in 2015 found that increases in import competition from China tend to reduce R&D and other forward-looking investments.[38]

Third, **management decisions to decentralize R&D, moving it to individual business units for the perceived advantage of being closer to the customer, often have the perverse effect of losing long-term strategic perspective.** Instead of providing long-term competitive advantage, R&D becomes just another cost center to be minimized.[39]

Finally, the availability of foreign research and engineering talent has grown substantially in recent years. **For some companies, moving R&D offshore is the high-skilled equivalent of moving production offshore for low-cost factory labor**. Controlling R&D costs is especially critical at a time when R&D productivity has fallen sharply. Between the 1960s and 2000s, research productivity fell

FIGURE 11: Advanced Technology Imports from China ($ Billions)



37 Chen, S. (2017, March 29). America's hidden role in Chinese weapons research. *South China Morning Post.* Retrieved from http://www.scmp.com/news/china/diplomacy-defence/article/2082738/americas-hidden-role-chinese-weapons-research

38 Arora, A., Belenzon, S., and Patacconi, A. (2015). *Killing the Golden Goose? The Decline of Science in Corporate R&D.* NBER Working Paper 20902. Retrieved from http://www.nber.org/papers/w20902

39 Knott, A.M. (2017). The real reasons companies are so focused on the short term. *Harvard Business Review.* Retrieved from https://hbr.org/2017/12/the-real-reasons-companies-are-so-focused-on-the-short-term

by a factor of eight.[40] As more researchers are required for a given objective, and the number and quality of foreign researchers increases, cost-conscious American firms are likely to continue to raise research spending abroad.

Recent data, as well as corporate announcements, illustrate changes in manufacturing R&D. The largest R&D spenders among manufacturers in 2017 were in the computer/electronics, pharmaceutical, and automotive sectors. Intel, which spent nearly $13 billion on R&D, was the only computer/electronics firms on the list that actually manufactures in the United States. Others, such as Apple and Cisco, spending $10 billion and $6.3 billion respectively on R&D, use Asian contract manufacturers and have no domestic production.[41] All have significant research centers abroad.

A few examples of major U.S. firms conducting R&D offshore include:

- Applied Materials, the world's largest supplier of semiconductor manufacturing equipment, built its largest research laboratory in Xi'an, China because researchers need to be close to the factories using the equipment. Government incentives to choose this location included a 75-year, discounted lease and 25 percent of operating costs paid for five years.[42]
- General Motors opened a large research center in Shanghai which serves as its center of global electric vehicle research because China is the world's largest market for electric vehicles. In 2017, China manufactured nearly 800,000 electric vehicles.[43]
- Intel has a large research center in Beijing for semiconductors and server networks because China is the biggest market for desktop computers and has the most internet users.[44]
- Apple announced two new R&D centers, in Shanghai and Suzhou, in 2017, joining centers in Beijing and Shenzhen. Apple committed to spend over $500 million on research in China focused on working with local partners to develop new technologies. China is Apple's largest overseas market and home to almost all of its product manufacturing.[45]

Relative decline in R&D by U.S. manufacturers, along with a greater emphasis on development, means that incremental innovation is the primary focus to make current products better, lighter, faster, and cheaper—all of which are essential to remain globally competitive. The federal government, on the other hand, invests mostly in long-term basic research. **American**

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40 The trend crosses multiple industries. For example, the number of researchers needed to double chip density in accordance with Moore's law is 18 times the number needed in the 1970s. Bloom, N.A., Jones, C.I., Van Reenen, J., and Webb, M. (2017). *Are Ideas Getting Harder to Find?* Stanford Business School Working Paper No. 3592. Retrieved from https://www.gsb.stanford.edu/faculty-research/working-papers/are-ideas-getting-harder-find

41 Bloomberg; Capital IQ. (2017). Ranking of the 20 companies with the highest spending on research and development in 2017 (in billion U.S. dollars). *Statista.* Retrieved from https://www.statista.com/statistics/265645/ranking-of-the-20-companies-with-the-highest-spending-on-research-and-development/

42 Bradsher, K. (2010, March 17). China drawing high-tech research from U.S. *The New York Times.* Retrieved from https://www.nytimes.com/2010/03/18/business/global/18research.html

43 Stanway, D. (2018, March 20). China electric car execs call for policy support, end to protectionism. *Reuters.* Retrieved from https://www.reuters.com/article/us-china-autos-electric/china-electric-car-execs-call-for-policy-support-end-to-protectionism-idUSKBN1GW0O0

44 Swanson, A., and Bradsher, K. (2010, April 30). China drawing H-T research from U.S. *The New York Times.* Retrieved from https://www.nytimes.com/2018/04/30/us/politics/trump-china-researchers-espionage.html

45 Gartenberg, C. (2017, March 17). Apple is opening two more R&D centers in China. *The Verge.* Retrieved from https://www.theverge.com/2017/3/17/14960534/apple-research-centers-china-shanghai-suzhou

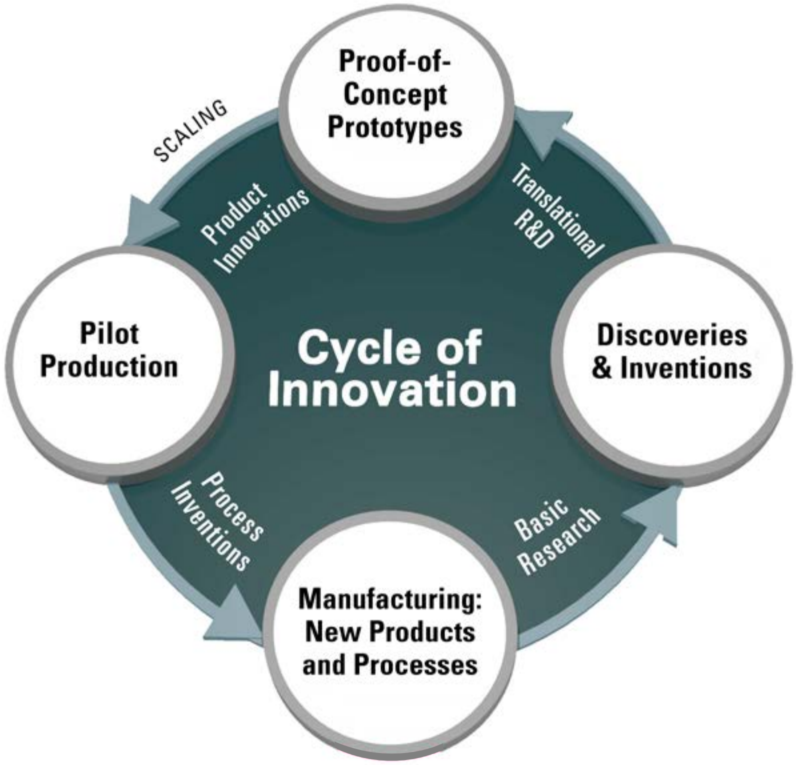
corporations rarely leverage the results of federal research to transition nascent but promising technologies into successful commercial products. In some cases, federal R&D funding supports technologies in which there is little if any domestic industrial production; advanced batteries are an example. Correcting this disconnect in the national innovation system is essential to long-term competitiveness. For both defense and commercial innovations, federal funding of university-performed R&D is becoming more critical to the national innovation system. Yet weaknesses in this part of the national innovation system negatively impact the national wealth that should be captured from this large investment in R&D.

BREAKDOWNS IN THE U.S. INNOVATION SYSTEM

The emerging shift in strategy by U.S. multinational manufacturers from “innovate here, manufacture there” to “innovate there, manufacture there” is creating challenges for the national innovation system that may not be fully recognized. Relative decline in domestic R&D spending by manufacturers puts more emphasis on government R&D to maintain the pace of innovation needed for future national competitiveness. Unfortunately, an innovation system that relies on government funding of university research is not well suited to maximizing commercialization of products. As central as university R&D is to the national innovation system, relatively little government-funded university-performed R&D is converted to national wealth through the production and sale of new products and application of new processes and methods. Technology transfer from national research laboratories is also weak. The system is not even structured to ensure that R&D results create national competitive advantage. A national strategy to nurture and leverage promising ideas has never been implemented, relying instead on market forces. From a global perspective, most R&D results from American universities are readily available to be commercialized elsewhere, but when viewed from a national perspective, the fruits of R&D have not sufficiently driven improvements to national wealth and security. Invention without production has been a consistent pattern for multiple mass market technologies in recent decades. For the sake of long-term growth and security, these shortcomings must be corrected at once.

Figure 12 illustrates the “cycle of innovation” typical for manufactured products. Basic research in science and engineering is one source of a myriad of discoveries and inventions, some of which are suitable for new product introductions, some for incremental improvements to existing products, and, of course, some that contribute to basic scientific understanding. Another equally important source of new inventions is the necessity to meet the challenges that arise from manufacturing at scale. New process

FIGURE 12: The Cycle of Innovation



technologies, quality and inspection methods, control technologies, and new products emerge from the manufacturing experience, depicted by the arrow from Manufacturing to Discoveries & Inventions. For those discoveries and inventions that could become new products and technologies, additional research—translational research—is necessary to demonstrate proof-of-concept. Typically, a prototype is built that operates under constrained laboratory conditions with sufficient functionality to file for patent protection. If the proof-of-concept is promising, a more functional prototype is developed and the design is refined for factors such as manufacturability, safety, reliability, cost-effective recyclability, and user interface. Then the production process is engineered, tested and refined in pilot production, and if successful, scaled to full manufacture of a new product or technology. Within a manufacturing company, new product sales produce the profits to fund the basic research that maintains the cycle. Within a research entity based in an academic institution or a federal laboratory, other steps are involved to move the invention into an existing company or a start-up firm created to commercialize it. How this cycle of innovation applies to university R&D is where the leakages become obvious, illustrating the shortcomings in the system, as well as opportunities to fix it.

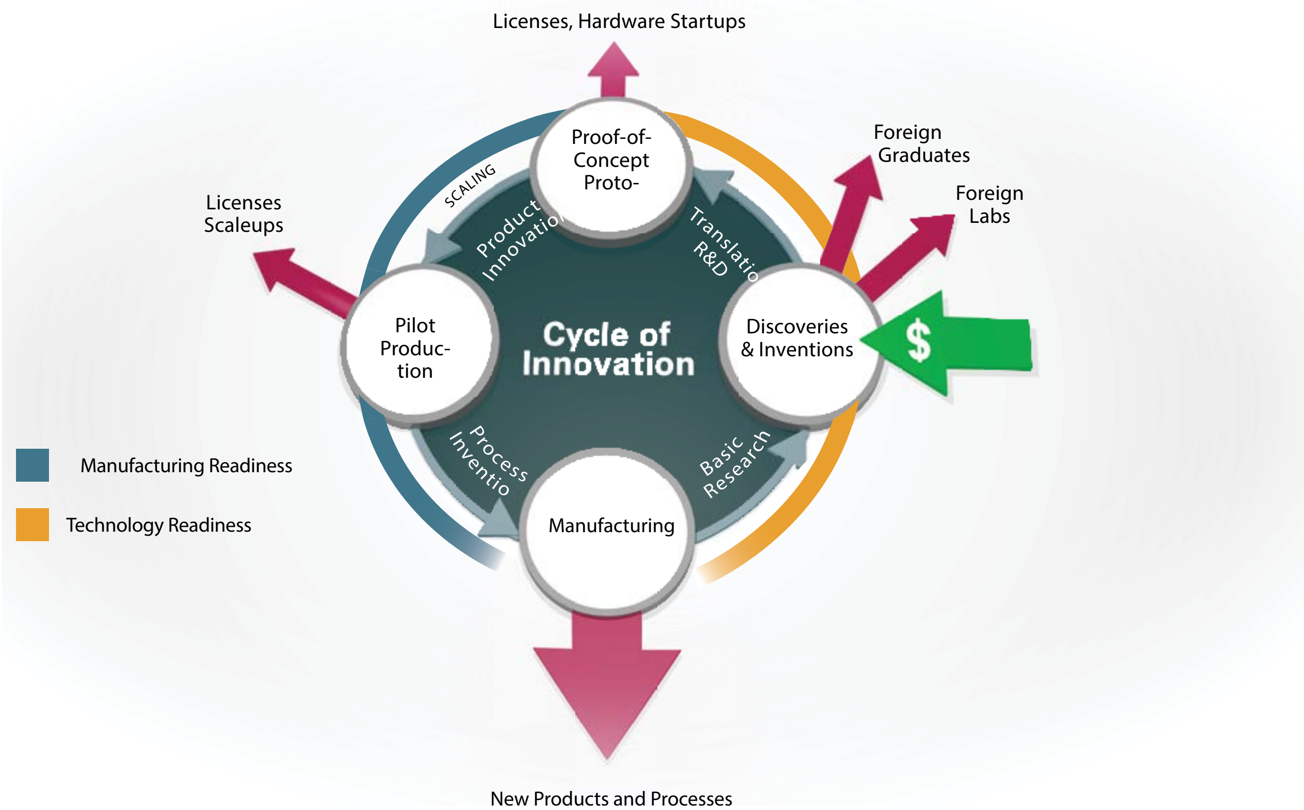
Figure 13 illustrates the same cycle of innovation, but highlights serious leakages in the U.S. innovation pipeline as it becomes more reliant on university R&D. The basic cycle is the same; however, at multiple steps along the way, either knowledge is lost, stagnates in the laboratory, or is commercialized abroad.

First, opportunity for foreign competitors to take advantage of research outcomes is, at the moment, a fundamental part of the system. Academic research, especially in science and engineering (S&E), is dependent on foreign graduate students, predominantly from Asia.

In 1966, foreign students received 23 percent of S&E doctorates; in 2015, foreign students received 56 percent of engineering doctorates, 53 percent in mathematics and computer science, and 44 percent in physics.[46] These graduate students are the hands-on researchers in university laboratories and therefore are most intimately familiar with the work, have the knowledge needed to recreate the work, and are best prepared to help commercialize the results.

Nationality would not matter if these graduates remained in this country. International students are eligible to work in the United States for a year after graduating, a period called Optional Practical Training. Graduates in science, engineering, technology, and mathematics (STEM) can work for an additional two years. After that, they are subject to the same visa lottery system as other immigrants. Historically, work visas have allowed many to stay.[47] Many have argued that foreign S&E graduates should receive permanent resident status (green cards) along with their diplomas,[48] a reasonable argument considering that immigrants have

FIGURE 13: Gaps in the Cycle of Innovation



U.S. Federal funding is largely restricted to maturing Technology Readiness Levels (TRLs) but not Manufacturing Readiness Levels (MRLs)

46 National Science Foundation. (2018). *Science & Engineering Indica*tors 2018. Retrieved from https://www.nsf.gov/statistics/2018/nsb20181/
47 The 2010 U.S. census found that 25 percent of the Bachelor's degree holders in STEM occupations are foreign born, as were just under half of all PhD holders.
48 The Border Security, Economic Opportunity, and Immigration Modernization Act, S.744 - 113th Congress, proposed eliminating numerical limits on immigrants who had earned a doctorate degree or a graduate degree in science, technology, engineering, or mathematics with an employment offer.

accounted for roughly 25 percent of the recent innovation activity in the U.S. economy.[49]

The predominance of foreign students in S&E graduate programs, and the growing tendency to return to their home countries, is also tied to the loss of the Industrial Commons in the United States and the shift of manufacturing R&D abroad. According to the NSF, in 2015 the job market for S&E doctorate recipients was the lowest since 2000, 4-13 points below its most recent peak in 2006.[50] With poor job prospects, U.S. students avoid graduate studies and foreign students return home even if they would prefer to stay.

However, foreign students are not the only source of leakage. In some cases, foreign institutions partner with American universities that are often encouraged to include foreign institutions in their research proposals. Engineering Research Centers (ERCs), funded by the NSF, have been an example, at least until recently. In other cases, foreign companies are members or participants in academic research centers. These firms may have significant presence, including manufacturing facilities, in the United States, and in some cases, may be essential participants for a center to access state of the art product and process technology. But they may also manufacture exclusively in their home countries, capturing the wealth generation and economic multiplier benefits at home. Nanotechnology, a national priority reflected in the creation of the National Nanotechnology Initiative in 2003, is a case in point.[51] The Japanese firm, Canon, established a U.S. affiliate, Canon Nanotechnologies, to partner with the NSF ERC for Nanomanufacturing Systems for Mobile Computing and Mobile Energy Technologies Display at the University of Texas. But Canon Nanotechnologies only conducts R&D; the nanotechnologies Canon licensed from the ERC are manufactured in Japan. Similar examples occur in other technologies such as displays, batteries, tissue engineering, and solar panels.

The process of funding academic research presents further opportunity for results to be captured by foreign companies. A typical faculty member receives funding from NSF and/or other federal agencies for an extended period of time to conduct basic research, often totaling several million dollars. Once a technology is proven to work even in a lab environment, the researcher will have difficulty maturing the technology further, for instance by testing prototypes in an operating environment, maturing manufacturing readiness or manufacturing at scale. After a few futile attempts to attract funding from the government or private sources, the researcher turns to (or is approached by) a foreign institute with money and facilities to establish a laboratory overseas. This happens quite regularly, with the loss of multiple promising technologies, all because the United States lacks strategy or a mechanism to fund nurturing and maturing of valuable results from the R&D that government funded in the first place.

Within the innovation cycle of university R&D, commercialization is dependent on licensing. However, interest in licensing depends on the research results demonstrating commercial feasibility through a proof-of-concept prototype, which requires translational research. **In many cases, funding for translational research**

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49 Kerr, W. (2007). The ethnic composition of U.S. inventors. *Harvard Business School Working Paper 08-006*. Retrieved from https://www.hbs.edu/faculty/Pages/item.aspx?num=20233

50 National Science Foundation. (2015). What are the postgraduation trends? *Science and Engineering Doctorates.* Retrieved from https://www.nsf.gov/statistics/2017/nsf17306/report/what-are-the-postgraduation-trends/job-market-science-and-engineering.cfm

51 U.S. Government Publishing Office. (2003). *21st Century Nanotechnolo*gy Research and Development Act. Retrieved from https://www.gpo.gov/fdsys/pkg/PLAW-108publ153/content-detail.html

is not readily available so many promising discoveries and inventions remain on the shelf or, at best, become side projects while the research team moves on to the next grant. This lack of translational research funding is another weakness in this innovation cycle.

Assuming the invention is sufficiently proven to attract licensing interest, negotiating a license is often overly complex, time-consuming, and expensive. Although some universities have relatively simple licenses with simple fees and royalties designed for start-ups, established companies perceive the licensing process to be difficult and therefore avoid it. Consequently, to a great extent, university inventions are licensed to start-ups specifically created to commercialize the technology. The start-up culture continues to grow, encouraged by hugely successful examples of companies emerging from universities.[52] Between 1980 and 2014, nearly 5,000 companies were launched from university research.[53] By one estimate, 30 percent of the value of companies listed on the NASDAQ stems from university-based, federally funded research, primarily due to the value of the intellectual property generated by the research.[54] Yet, for manufacturing start-ups striving to commercialize hardware products, the challenges are significant, especially with a goal of building a manufacturing business in this country (see Investment Capital for Hardware Start-ups).

Even when hardware start-ups receive venture funding, it typically does not include the funds needed to scale production, the next step in the innovation cycle and another source of weakness. MIT's study, *Production in the Innovation Economy*, examined 150 production-related hardware start-ups emerging from MIT research. The study found that these start-ups had access to sufficient skills and financing for R&D and initial product demonstration, but when the time came to scale production to commercial levels, the need for additional capital, production capabilities, and lead customers pushed many of these firms to move production abroad, usually to China.[55] Other studies have documented a slowdown in the formation of new manufacturing start-ups and continuing stagnation in their ability to scale production.[56]

China's network of suppliers, skills, and customers is strong, responsive, and easy to work with. Numerous American consultancies facilitate this process at every stage; Dragon Innovation in Boston and PCH International in San Francisco are examples. In many cases, Chinese investors provide the needed capital to make the move offshore, or to buy the U.S. start-up outright. Often, these purchases provide access to advanced technologies that provide competitive advantage to the buyers that is then lost in this country.

Part of what makes Chinese production attractive is the willingness of Chinese investors to accept the risk and producers to access whatever manufacturing processes are necessary to produce the new technology, even developing new processes if needed. Except in specialized cases,

52 Google's initial public offering in 2003 returned over $330 million to Stanford University.
53 Belz, A. (2016). Trends in industry-university research relationships. *A Vision for the Future of Center-Based, Multidisciplinary Engineering Res*earch. Washington, DC: The National Academies Press. Retrieved from https://www.nap.edu/catalog/23645/a-vision-for-the-future-of-center-based-multidisciplinary-engineering-research
54 Ibid.
55 Reynolds, E.B., Samel, H.M., and Lawrence, J. (2014). Learning by building: Complementary assets and the migration of capabilities in U.S. innovative firms. In R.M. Locke & R.L. Wellhausen (Eds.), *Production in the Innovation Economy.* Cambridge, MA: MIT Press.
56 Bonvillian, W.B., and Singer, P.L. (2018). *Advanced Manufacturing: The New American Innovation Policies.* Cambridge, MA: MIT Press.

for instance when a technology is defense related, neither universities nor hardware start-ups have sufficient funding to increase the manufacturability of new technologies, the Manufacturing Readiness Level (MRL). Fabricating a few prototypes is not the same as manufacturing at scale. Basic fabrication can often be demonstrated in the laboratory, but determining the detailed design attributes and the engineering architecture needed to scale to volume manufacturing requires additional research. **Raising the MRL from capability to produce in the laboratory (MRL 4) to capability to produce in a production-representative environment with most of the specifications clearly defined (MRL 7) would be a boon to start-ups and other licensees and increase domestic alternatives to Chinese production.** It requires significant investment in creating pilot production facilities, which is typically too risky and expensive for venture capital investors; large multinational manufacturers tend to show interest only after higher TRLs and MRLs are achieved; and currently there is no federal S&T agency that funds the necessary translational research or invests in maturing MRLs.

Finally, the importance of the linkages between manufacturing and the research that leads to new discoveries and inventions must not be overlooked. The knowledge gained by manufacturing includes both knowledge about the production process and about the products being produced, both of which help to define questions to be tackled by research. This is the basis for the growing trend to locate research activities near the offshore factories reside, to be near the knowledge and the questions. By not manufacturing, the United States is losing ground in a range of industries—displays, energy storage, drones, solar cells, for example—that are important to national security and future commercial industries.

Investment Capital for Hardware Start-ups

The venture capital industry in the United States is the world's largest and most robust, well-recognized for its critical role in the national innovation system. As important as it is, venture capital is rarely invested in manufacturing and, in fact, is ill-suited for hardware start-ups that need long-term, patient capital to ensure success.

Since 2002, both the number of deals and the amount invested by venture capital funds in manufacturing have averaged just 0.4 percent. The dollars invested exceeded 1 percent of the total (barely) only twice, in 2008 and 2009.[57] Figure 14 illustrates the distribution of venture capital investment by market sector in 2017.

The reasons so little venture capital is invested in manufacturing start-ups are simple: cascading risks and time. Compared to the most common alternatives in software and biotechnology, manufacturing new, unproven products confronts risks at multiple points. Will the product work as intended? Can it be manufactured profitably? Are needed suppliers available at the right cost and delivery time? Will customers buy it in sufficient quantities to justify the needed capital investment? Obviously, many of these challenges face software and biotechnology start-ups, but the investments required to rapidly scale software are much lower than hardware.[58] The operational costs

57 Explore data at PWC, https://www.pwc.com/us/en/industries/technology/moneytree/explorer.html#/%20type=history&category=&currentQ=Q1%202018&qRangeStart=Q1%202013&qRangeEnd=Q1%202018&chartType=bar

58 Bonvillian and Singer describe why VCs are drawn to software and biotechnology in *"Innovation Orchards": Helping Tech Start-Ups Scale* from ITIF (2017), available at https://itif.org/publications/2017/03/27/innovation-orchards-helping-tech-start-ups-scale

FIGURE 14: U.S. Venture Capital Investments by Sector, 2017

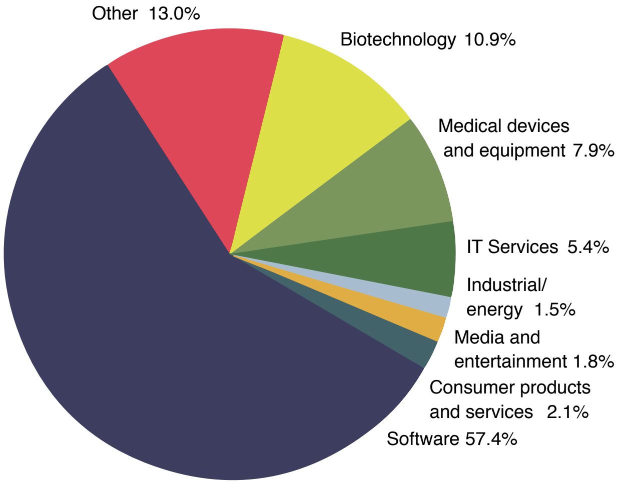
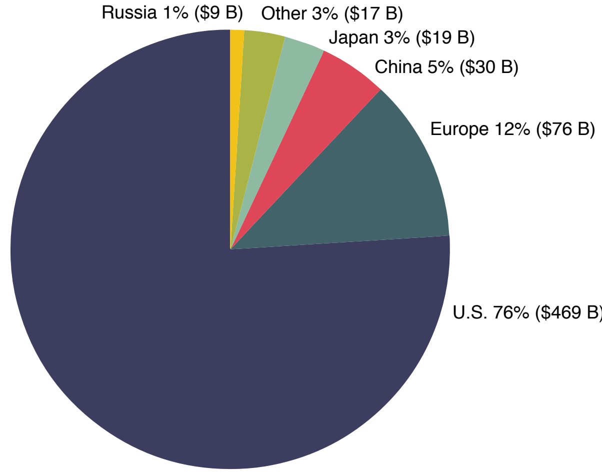


FIGURE 15: Foreign Participation in the U.S. Venture Capital Market, 2017



to launch a software company declined by an estimated factor of 100 between 2000 and 2010. As a result, **private capital markets skewed strongly toward software: software attracts capital at a rate of roughly 7:1 compared to industrial opportunities, compared with roughly 2:1 twenty years ago.**[59]

Although venture capital has a history of funding favored industries in waves—the current wave favors artificial intelligence start-ups—a review of a few recent hardware start-ups helps to explain the relative lack of interest. According to CB Insights, the seven largest consumer hardware start-ups in recent years were Jawbone, NJoy, Juicero, Fuhu, Pebble, Zeebo, and hello. Between them, they raised nearly $1.5 billion. Four went bankrupt and three were purchased: Pebble sold to Fitbit; Fuhu, a tablet maker, sold to Mattel; and NJoy, an e-cigarette maker, was purchased by Homewood Capital.[60] At least in this consumer hardware industry segment, success has been far from assured.

The U.S. venture capital market is also becoming more international, with foreign-based funds capturing a growing share of the market, reaching nearly 25 percent of the market. Figure 15 illustrates this foreign participation in 2017. Foreign investment in and purchases of U.S. start-ups has raised concerns in some sectors.[61] For example, Chinese investment in Neurala, a Boston-based artificial intelligence start-up with technology to make robots more perceptive, raised alarms in government circles, but Neurala had been unsuccessful raising government or private U.S. capital. Investments in other firms developing technologies with potential military applications, such as rocket engines, sensors for autonomous vehicles, and flexible electronics have also raised concerns among U.S. military officials.[62] The aerospace industry has been particularly attractive to Chinese investors with multiple deals made in recent years (Figure 16).[63] At least partially to counter this weakness in the private venture capital market, state governments, universities, and

59 Belz, A. (2016). Trends in industry-university research relationships. *A Vision for the Future of Center-Based, Multidisciplinary Engineering Research.* Washington, DC: The National Academies Press. Retrieved from https://www.nap.edu/catalog/23645/a-vision-for-the-future-of-center-based-multidisciplinary-engineering-research

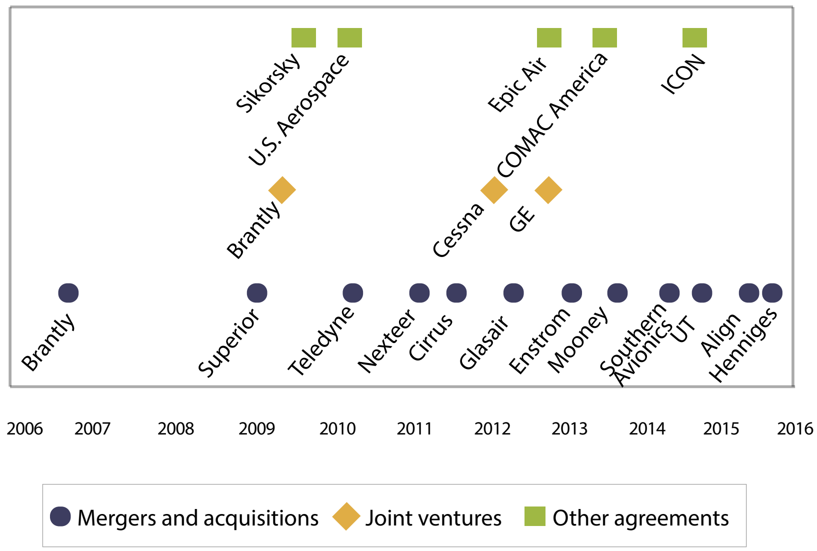
60 CB Insights. (2017). *The Top 9 Reasons Hardware Startups Fail.* Retrieved from https://www.cbinsights.com/research/report/hardware-startups-failure-success/

61 Sprinkle, T. (2017) Strings Attached. *Mechanical Engineering, 139*(05), 32-37. http://doi.org/10.1115/1.2017-May-1

62 Mozur, P. and Perlez, J. (2017, March 22). China bets on sensitive U.S. start-ups, worrying the Pentagon. *The New York Times.* Retrieved from https://www.nytimes.com/2017/03/22/technology/china-defense-start-ups.html

63 Ohlandt, C., Morris, L., et. al. (2017). *Chinese Investment in U.S. Aviation.* Santa Monica, CA: RAND Corporation.

FIGURE 16: Chinese Investments in the U.S. Aerospace Industry



non-profit organizations have established small angel and venture funds. Usually established as part of a state's economic development efforts, these funds have a mixed record of success, usually due to investment decisions based on political expediency rather than rigorous technological and market assessment. However, many have navigated sometimes conflicting objectives to achieve long-term success. Some of the larger public venture funds include Connecticut Innovations, Elevate Ventures (Indianapolis), Innovation Works (Pittsburgh), TMCx Innovations (Houston), TEDCO (Maryland), and Rev1 Ventures (Columbus, Ohio). These funds typically restrict funding to start-ups established in the local state or region, often as university spin-offs. Among the larger funds, they are more likely than private venture capitalists to invest in hardware, production-oriented start-ups, averaging roughly 20 percent of their portfolios.[64] Some examples include:

- The Oregon Nanoscience and Microtechnologies Institute leveraged Portland's historical strength in the semiconductor industry to create a new state-wide cluster, including gap funding (via two programs offering $75,000, then $250,000) to support nascent materials science ventures.
- The Georgia Research Alliance (GRA) has made more than $600 million in investments, providing funding to university spin-offs in phases, which can include equity investments by the GRA Venture Fund of more than $1 million.
- The Engine, started at MIT in 2016, provides affordable workspaces, access to specialized equipment, efficient business services, and patient capital to start-ups in biotechnology, robotics, manufacturing, medical devices, and energy.[65]
- SC Launch, a non-profit division of the South Carolina Research Authority, provides grants, loans, and direct investments to start-ups, along with mentoring and networking. Funding is provided through a combination of private donations and sales of state tax credits up to $6 million annually. Its portfolio includes 164 companies, roughly 40 percent of which are manufacturers.[66]

64 Internal analysis conducted on data gathered from PitchBook, https://pitchbook.com/
65 Matheson, R. (2016, October 26). MIT launches new venture for world-changing entrepreneurs. *MIT News.* Retrieved from https://news.mit.edu/mit-announces-the-engine-for-entrepreneurs-1026
66 Interview with Jill Sorensen, Director of Entrepreneurial Programs for SCRA.

Incubators and accelerators, often with public funding support, are also an important part of the start-up landscape. Some, such as Greentown Labs in Boston, have targeted programs for hardware start-ups, working closely with the local MEP to find local manufacturers with production capabilities to partner with start-ups. Others have ties to local universities, especially engineering schools. Some include maker spaces, typically 3D printers but sometimes other CNC machine tools, that start-ups can use to perfect prototypes and address manufacturing issues. The support and infrastructure provided by incubators can help hardware start-ups make progress faster, but they still face issues in scaling production, which is often most easily done in China.

Corporate venture capital (CVC) funds are also becoming more common among large manufacturing companies. More than 1,000 CVCs were active in 2017 with the 10 most active being Google Ventures, Intel Capital, Salesforce Ventures, Qualcomm Ventures, GE Ventures, and Microsoft Ventures. Two Chinese funds, Legend Capital and Fosun RZ Capital, and two South Korean funds, K Cube Ventures and Samsung Ventures, round out the top 10.[67] Within specific sectors, such as autonomous vehicles, the CVC funds of large suppliers, including Bosch, Delphi, and Magna, have made investments and acquisitions in the full range of relevant technologies: radar, lidar, and optical sensors; artificial intelligence and data analysis software for autonomy; and connected vehicle cybersecurity.[68]

Even including the investments by public and corporate funds, hardware start-ups receive much less attention and less funding than firms in other sectors, especially relevant to the capital needed to scale production to commercial volumes. It is evident that, at least for hardware start-ups, the U.S. system of starting companies based on publicly funded research results, simply does not work. **Despite fundraising innovations such as Kickstarter and other crowdfunding mechanisms, expecting hardware start-ups to raise seed, angel, and venture funding to perfect their product, and then raise more funds to fully commercialize the product with production in the United States is a tall order that few achieve.**

Insufficient capital is available for hardware companies; in too many cases, needed production expertise and capacity are not obtainable because of the lost Industrial Commons; and inputs such as components, subassemblies, and test equipment are not available domestically. To build production capacity in the United States, the best option often is to sell to larger American manufacturers, but this option is only available if the start-up's product or technology meets a need of a larger firm. Many do not. Too frequently, the easiest option is to move production offshore, usually to China.

All of these breaks in the national innovation cycle mean that the United States is failing to capture all of the national wealth that should be created from what remains the world's largest national investment in R&D. In fact, U.S. R&D is benefiting the manufacturing sectors of competing nations. With a clear recognition of these leakages in the innovation cycle, targeted investments are necessary to fix the cycle, commensurate with the importance to future national security and economic prosperity.

67 CB Insights. (2018, February 28). *The most active corporate VC firms globally.* Retrieved from https://www.cbinsights.com/research/corporate-venture-capital-active-2014/
68 Ibid.

TRANSFORMATIONAL MANUFACTURING TECHNOLOGIES

The emergence of new technologies is creating opportunities, perhaps even an imperative, to rebuild U.S. manufacturing competitiveness in advanced technologies. Cross-cutting technologies and advanced materials are impacting multiple industries in ways that advantage domestic production. At the same time, product and process technology shifts in specific advanced industries, including pharmaceuticals and semiconductors, are creating opportunities to leapfrog existing standard practice. Successful firms will be capable of rapidly adapting their physical and intellectual infrastructures to exploit changes in technology as manufacturing becomes faster and more responsive to changing global markets. With supportive government policies and appropriate investments, U.S. manufacturing can regain leadership, rebuild the Industrial Commons, capture all the benefits from the nation's R&D spending, and comprehensively meet national security requirements.

Smart Manufacturing

The broadest and most impactful transformative change affecting manufacturing is the application of powerful computing, networking, sensing, data analytics, machine learning, and artificial intelligence. Collectively known under various monikers—Smart Manufacturing, Industry 4.0, Industrial Internet of Things (IIOT)—**the digitalization of manufacturing is creating profound shifts in where and how production is done and participation in global value chains.** Combined with advanced materials, nanotechnology, sustainability, rapid product cycles, and other market forces, future manufacturing will be vastly different from the mass production, cost minimization strategies that have driven decisions for the past three decades. Smart manufacturing creates the opportunity to re-establish domestic production in advanced industries, providing competitive advantages from increased efficiency, security, rapid response to customer demand, and new product features incorporating sustainability and resource optimization. **Value will be derived from time to market, response to demand changes, inventory optimization, asset utilization, resources optimization, and quality improvement, rather than the simple cost minimization strategies that have driven offshore production.** The challenge for U.S. industry will be to deploy the relevant technologies quickly and effectively and to adapt business models to take advantage of these new capabilities.

Smart manufacturing encompasses a range of technologies implemented on the factory floor, in the communication networks between producers and consumers to integrate supply chains, and in all the logistics, financial, and management systems that pervade all levels of industrial production. A few of the critical technologies include:

Product development: Sophisticated computer-aided engineering tools, including optimization, design for manufacturing, material selection and certification, statistical design of experiments, data analytics and virtual reality tools are increasingly used to design and develop new products to reduce product introduction failures, reduce product development costs and to meet custom market niches. Accelerating product development is the top priority, so far, for firms using 3D printing.[69] Incorporating smart technology features into products will also be important as connectivity, self awareness, and interactivity become expected by consumers.

Distributed manufacturing: Contract manufacturing using Asian contractors has become standard operating procedure in electronics and other industries, and machine shops used to make parts have always been a major part of supply chains. However, advances in production technologies, such as rapid injection molding, additive manufacturing and CNC milling (subtractive manufacturing) are expanding opportunities for local production of custom parts and final products. Companies such as Xometry, based in Maryland, ProtoLabs, based in Minnesota, and Fictiv in San Francisco offer on-demand manufacturing services based on digital part designs uploaded by customers.[70] Software Defined Manufacturing is an emerging cloud-based distributed manufacturing concept, supported by IBM and others, in which a part design is shared with a community of manufacturers who identify an optimal producer that can meet time and volume requirements.[71]

Integration of Operational Technology (OT) and Information Technology (IT): OT/IT integration is central to smart manufacturing. Multiple benefits include dramatic increases in capacity utilization, from a current average of roughly 60 to 85 percent and more. Sensors on production equipment (often retrofittable) tracking parameters such as temperature, vibration, and current load, combined with effective analysis of the resulting data, are enhancing predictive maintenance resulting in much higher machine uptime. For example, a Michigan manufacturer increased uptime 20 percent by applying sensors to monitor tool

69 Sculpteo. (2018). *The State of 3D Printing 2017.* Retrieved from https://www.sculpteo.com/media/ebook/State_of_3DP_2018.pdf

70 https://www.xometry.com/; https://www.protolabs.com/; https://www.fictiv.com/

71 Breitgand, D. (2014). Collaborative manufacturing as a service in the cloud. *IBM Research.* Retrieved from https://www.ibm.com/blogs/research/2014/12/collaborative-manufacturing-as-a-service-in-the-cloud/

wear on the shop floor.[72] New business models are also emerging in which equipment providers use performance-based contracting to guarantee uptime, enabled because of the data generated by the sensor-laden equipment.

Edge Computing: To take advantage of the computational power of cloud computing while avoiding its inherent latency, edge computing is emerging as a an effective means to process sensor data locally for real-time production control, then, when necessary, passing batch data to the cloud for in-depth analysis. Companies such as Saguna Networks specialize in edge computing. Other firms, such as Mocana[73] and Rubicon Labs[74] (both in San Francisco), specialize in secure communications from sensors and industrial control systems to the cloud to address cybersecurity issues.

Automation and robotics: Industrial robots are experiencing rapid advances in capabilities due to improved sensors, manipulators, control systems, connectivity, and processing power. Currently, three-quarters of industrial robots are used in just four industries: transportation equipment, machinery, computers and electronics, and electrical equipment, appliances, and components. Roughly 80 percent are used in five countries: China, Germany, Japan, South Korea, and the United States, with China significantly ahead. Use of industrial robots has grown nearly 20 percent in recent years, with most of that growth in Asia.[75] However, U.S. shipments of industrial robots reached a record high in 2017 and continued strong performance through early 2018.[76] One recent innovation is collaborative robots ("cobots"), easily reprogrammable robots that work alongside production staff without being enclosed in a safety cage. Rethink Robotics, headquartered in Boston, is a leading cobot manufacturer with easy-to-train, quickly deployable robots used in a wide range of applications and industries including packaging, machining, and inspection. Relatively inexpensive, one manufacturer estimates that its robots pay for themselves in less than 200 days.[77]

Additive manufacturing: Also known as 3D printing, additive manufacturing is beginning to move from models and basic prototypes to production of parts with complex geometries. The additive manufacturing industry is making strides toward mass production applications, which will have broad impacts on tooling costs, materials, supply chains, and logistics. GE Aircraft Engines, for example, has used metal additive manufacturing to reduce part counts and build an engine that is 15 percent more fuel efficient. UTC Aerospace Systems is using metal additive manufacturing across a range of materials to reduce weight, part counts and lead times up to 80 percent.[78] Adidas has partnered with Carbon to mass produce 3D-printed custom shoes. General Motors is working with

72 Hitch, J. (2018, March 22). Adopt or Die: AI Leaves Manufacturing No Choice*. Industry Week.* Retrieved from http://www.industryweek.com/technology-and-iiot/adopt-or-die-ai-leaves-manufacturing-no-choice
73 https://www.mocana.com
74 https://www.rubiconlabs.io
75 International Federation of Robotics. (2017). *World Robotics 2017 Industrial Robots.* Retrieved from https://ifr.org/free-downloads/
76 Robotic Industries Association. (2018, February 26). Robotics, vision and motion control industries set new growth records in 2017. *Robotics Online.* Retrieved from https://www.robotics.org/content-detail.cfm/Industrial-Robotics-News/Robotics-Vision-and-Motion-Control-Industries-Set-New-Growth-Records-in-2017/content_id/7019
77 Universal Robots A/S. (2017, July 20). Universal robots saves 9 hours of production time at Glidewell Laboratories. *Robotics Online.* Retrieved from https://www.robotics.org/content-detail.cfm/Industrial-Robotics-Case-Studies/Universal-Robots-Saves-9-Hours-of-Production-Time-at-Glidewell-Laboratories/content_id/6638
78 Canaday, H. (2018, May 14). UTC aerospace working vigorously on additive metal parts. *MRO Network.* Retrieved from http://www.mro-network.com/manufacturing-distribution/utc-aerospace-working-vigorously-additive-metal-parts

Autodesk to increase the number of production-ready parts made with additive technology. For example, a 3D-printed stainless steel seat bracket is 40 percent lighter and 20 percent stronger than its predecessor, replacing eight components and multiple suppliers with just one.[79] A number of start-ups promise to increase the catalog of materials that can be used in additive manufacturing including a broader range of metals and carbon fiber composites.[80]

New business models are emerging, based on many of these technologies, that allow SMMs to access powerful tools such as modeling and simulation on a pay-per-use basis, lowering cost, simplifying access, and increasing flexibility. **The computational power of the cloud eliminates the need for specialized and expensive hardware and software, thereby lowering barriers to entry for SMMs.** Intelligent design tools are one emerging technology available through the cloud, in which the software detects design aspects that are not manufacturable and suggests alternate solutions or, in some cases, only creates designs that are easily manufacturable. Autodesk's Simulation 360 is one such example.

Other business models are also emerging that provide an opportunity to regain domestic production in the context of a changing manufacturing environment. For example, Manufacturing as a Service (MaaS) takes contract manufacturing steps further, relying on shared use of a networked manufacturing infrastructure. As more manufacturing infrastructure—everything from design software, production planning, and equipment—becomes networked, demand for more products of more variety can be met without owning any producing equipment. The results should be lower costs, greater machine utilization, more capacity, and more options for materials use, product features, and cost-effective low-volume custom production.

Disruptive technologies in individual industries are also creating opportunities for the United States to establish, or re-establish, strong positions. In some cases, these technologies are in industries with important national security implications, such as semiconductors and pharmaceuticals.

System-in-Package

Semiconductor packaging moved offshore in the 1980s because it was labor intensive. Now fully automated, emerging packaging technologies, System-in-Package (SiP), are creating an opportunity to restore domestic packaging operations, a big step in recapturing control of the advanced semiconductor value chain.

Currently Intel and GLOBALFOUNDRIES operate the most advanced semiconductor fabs in the United States; both ship completed silicon wafers to Asia for packaging. Continuing progress in reducing feature sizes, with the frontier now at 7 nanometers and below, integration of multiple functions as System-on-Chip (SoC), and three-dimensional integrated circuits are all defining the state of the art.[81] SiP is a complementary technology to SoC in which multiple silicon chips are placed in a single

79 Carey, N. (2018, May 3). GM bets on 3D printers for cheaper and lighter car parts. *Reuters.* Retrieved from https://www.reuters.com/article/us-general-motors-parts/gm-bets-on-3d-printers-for-cheaper-and-lighter-car-parts-idUSKBN1I408K
80 CB Insights. (2017, December 28). Corporate investments drive a new wave of industrial 3D printing. Retrieved from https://www.cbinsights.com/research/corporate-investment-industrial-3d-printing/
81 Wessner, C., and Howell, T. (2018). *Partnering to Grow the New York Regional Nano-Cluster,* Washington, DC: Georgetown University.

package and connected using wire bonds or solder bumps to reduce the overall system size. Firms such as Apple are using SiPs to mix multiple components—central processors, logic, analog, and memory—into a single package.[82]

Packaging started as a manual process, but is now largely automated. It continues to be located in Asia because of the experience base—the Industrial Commons for this activity—resides in the leading packaging firms that have refined processes since the 1980s. **The emergence of SiP and continued advances in the technology creates an opportunity to re-establish packaging capability in the United States as existing packaging facilities become obsolete.** With appropriate incentives, SiP operations could be built near U.S. existing fabs, which could then create advantages to establishing circuit board assembly plants nearby, too. By taking advantage of a discontinuous technology, SiP, much more of the semiconductor value chain could be rebuilt in this country with positive impacts on defense electronics and most other hardware sectors as digitalization becomes pervasive.

Continuous Manufacturing of Pharmaceuticals

Solid format pharmaceuticals are typically a batch production process. Combinations of active and inert ingredients are combined in carefully measured proportions, then fed into pill-forming or capsule-filling machines to prepare batches of final product. Many steps in this batch production process take time and create the possibility of mistakes. Multiple production lines increase the volume and variety of production, but also multiply the risk of quality defects. Plus, mixers, feeders, and other equipment must be cleaned between batches to avoid cross-product contamination. Batch production is relatively labor-intensive, which helps to explain why so much manufacturing, especially of generic drugs, is done in China and India.

Continuous manufacturing (CM) methods for powder-based pharmaceuticals eliminates batch processing for much faster, more reliable production through an uninterrupted process. CM can shorten production times, allows for more precise production control, and reduces the likelihood of errors and production breakdowns. The technology can be used for an entire production process or for specific operations within a larger process. The Center for Structured Organic Particulate Systems (C-SOPS) at Rutgers University, in partnership with other universities and industry, has been a leader in the development of CM technology.[83]

Congress recognized the potential offered by CM for drug production, enacting the "21st Century Cures Act" in 2016, which authorized grants to support continued development of CM. The Food and Drug Administration (FDA) encourages firms to adopt CM, provides technical assistance, and has issued guidance to industry wanting to implement CM and other technologies.[84] A growing number of manufacturers, including Lilly, Vertex, and Janssen Pharmaceutical Companies, are using CM. **As precision medicine and rapid response to patient needs become more important, CM can create competitive advantages for domestic production of**

82 Shih, W. (2018). *Can an integrated semiconductor manufacturing capability be restored in the United States?* Unpublished manuscript. Harvard Business School, Cambridge, MA.
83 http://www.csops.org/
84 FDA. (2017). *Advancement of emerging technology applications for pharmaceutical innovation and modernization, guidance for industry.* Retrieved from https://www.fda.gov/downloads/Drugs/GuidanceComplianceRegulatoryInformation/Guidances/UCM478821.pdf

pharmaceuticals and, in the future, other high-value chemicals.

These are just a sample of the technologies already in use or emerging that will have profound effects on where, how, and how much manufacturing takes place. **The United States has an opportunity to take a leadership role, especially since many of these technologies rely on U.S. strengths in design, software, and networking. But capturing the competitive advantages requires broad-based dissemination and implementation of the enabling technologies.** Although there is strong evidence that implementation of smart technologies exceeds expectations for efficiency gains and return on investment, relatively few manufacturers have made serious inroads to implementation. Lack of knowledge, fear, skill availability, and focus on the daily pressures to meet production targets prevent SMEs from moving more rapidly.

Leadership in smart manufacturing should be considered a national priority and should be addressed with targeted programs and policies that will accelerate implementation. These would include mobilizing expertise; providing financial resources to buy technology; accelerating development of needed standards; and identifying a clear glide path for technology implementation appropriate for different firms in different industries of different sizes. Federal, state, and local governments have a role, along with trade associations and other industry groups. Some are already making strong contributions. Automation Alley in the Detroit region is one example.[85]

Because smart manufacturing will eventually be pervasive and essential to both national economic strength and national defense, it is important that the enabling technologies be produced domestically, including not only design but also manufacturing. Sensors, controllers, networking, and the other hardware requirements for data analysis and machine intelligence are too important to rely on foreign sources. From a security perspective the same principles currently being applied to drones and telecommunications equipment from Chinese providers ZTE and Huawei should be applied to smart manufacturing. From a competitiveness perspective, these smart manufacturing technologies will evolve and the most effective way to ensure both continuous improvement and first mover advantages in technology implementation will be to manufacture the enabling electronics domestically.

U.S. manufacturing needs to get in front of the wave of change created by disruptive technologies. Markets are changing as consumers want instant gratification. Intelligent technology is pervading whole sectors: autonomous vehicles, drones, distributed energy and intelligent grids, and all areas of defense production, to name a few. The United States has been ahead in performing the research that creates the technologies that enables all of these changes, but has not maintained production capabilities to capture global markets, value added, and wealth creation. This failure has impacted the long-term health of the economy and national security. **By increasing the pipeline of new products, investing in the necessary manufacturing capabilities to make those new products, and incentivizing broad-based implementation of smart manufacturing technologies, the United States can recapture its manufacturing leadership.**

85 https://www.automationalley.com/


BOLD STRATEGY AND CRITICAL NEXT STEPS

U.S. manufacturing is on the cusp of a new era. In contrast to recent decades in which the focus has been on globalization, cost reduction, and lean production, the coming decades promise a much more responsive, flexible, and intelligent manufacturing sector. Advances in a myriad of technologies ranging from high-performance materials to ubiquitous sensors, from self-correcting robots to autonomous factories, will transform both products and processes. The United States is well-placed to take advantage of the opportunities created by these technological advances, building on strengths in research at world-class universities, software development, systems integration, creativity, and innovation. **But taking advantage and recapturing industrial leadership will require national recognition of the importance of manufacturing and a focus on building the industries of the future.**

Unlike many competing nations, the United States does not have a national manufacturing strategy. Countries such as Germany, South Korea, Japan, and China have manufacturing strategies with long-term R&D programs, investments in infrastructure, and national goals for specific industries. The details vary, but common themes include maintaining a strong industrial research infrastructure and vocational education system, and building sustained competitive advantage in important export industries. Public-private partnerships are usually important mechanisms. **Although the United States has many government programs, at both the state and federal levels, they are neither coordinated nor funded to translate basic research into U.S-based manufacturing, do not include meaningful metrics, and tend to devolve to short-term problem solving rather than long-term strategy.** Most federal S&T agencies do not invest in manufacturing research to advance process technologies and innovations in manufacturing machines and equipment.

Instead, the U.S. approach relies on market-based decisions, which for most large manufacturers, have been based on cost reduction and quarterly earnings. Over time, the result of myriad decisions has resulted in a "hollowing out" of U.S. industry as production was moved offshore. U.S. manufacturers first moved to reduce labor costs, then to build production in growing foreign markets, and then to take advantage of skills and supplier capabilities that are often in short supply here. The long-term negative ramifications of this shift of production abroad are now apparent, creating a number of "grand challenges" that must be addressed to restore U.S. manufacturing, especially in advanced technologies critical to national security and prosperity. These manufacturing grand challenges include:

1. Rebuild the Industrial Commons

The United States has lost fundamental production skill and capabilities—the Industrial Commons—in many industries and has lost entire industrial sectors, with noticeable impacts on the national innovation system and growing adverse effects on the defense industrial base.[86] Production can provide competitive advantages that are difficult to copy and have long-term sustainability. Maintaining domestic manufacturing capabilities is essential to retaining the know-how needed to produce next generation technologies, and to retaining critical defense production.

2. Convert national R&D to national wealth and security

Leading the world in R&D spending is not sufficient to ensure prosperity. Technologies invented here are being licensed, sold, or given away to manufacture overseas, which, in effect, is subsidizing R&D for other countries. The results of R&D must create new products, including defense critical technology products, that can be made in America at commercial scale to generate wealth, jobs, and exports.

3. Lead emerging industries

To ensure future economic strength and defense superiority, the United States must have a leadership position in emerging industries such as autonomous vehicles, robotics, metal-additive manufacturing, bio-manufacturing, energy storage, advanced materials, and quantum computing, to name a few. Dependence on foreign suppliers, regardless of how much cheaper they may be, is creating defense vulnerabilities and long-term competitive disadvantages.

Bold steps are needed to ensure that these challenges are met quickly and vigorously. Market forces alone are unlikely to achieve the needed change. They have not so far. With sustained, strategic investments, the United States can regain fundamental manufacturing capabilities, ensure a return on federal investments in R&D, capitalize on technology changes broadly affecting manufacturing, establish leadership in new industries, and restore the broad-based supplier networks that are essential to economic and national security.

Restoring U.S. manufacturing leadership and, perhaps more importantly, restoring the nation's ability to capture wealth from the national innovation system with a robust manufacturing base, is a challenge to both the private and public sectors. Manufacturers, driven by short-term financial incentives, primarily focus on the current product development through incremental innovation while abandoning the long-term translational R&D needed to mature basic research results into a "next big thing."

86 For recent examples, see Mehta, A. (2018, May 22). America's industrial base is at risk, and the military may feel the consequences. *Defense News*. Retrieved from https://www.defensenews.com/pentagon/2018/05/22/americas-industrial-base-is-at-risk-and-the-military-may-feel-the-consequences/

Only government can overcome this market failure and enable the United States to remain globally competitive.

The nation must be aggressive in meeting the grand challenges and pursuing the opportunities created by rapid technological change, for the sake of wealth creation and national security. Rebuilding the Industrial Commons, performing the translational research necessary to fully commercialize basic research results, and incentivizing the widespread adoption of smart manufacturing and other advanced technologies are all areas in which the role of government is paramount. A few new programs will not suffice; they haven't in the past. Bold new initiatives with long-term commitment will make the difference.

Paramount for government is to make investments in manufacturing research, process technologies and innovation, and systems engineering. The impact will be:

- wealth is created from public R&D;[87]
- domestic industry, especially SMMs, implements advanced technologies faster than foreign competitors;
- defense production capabilities are maintained and foreign dependence minimized; and
- the skills and knowledge needed at all levels of industry and the national research enterprise are readily available.

Critical Next Steps

The United States needs a broad national conversation to identify the necessary steps to achieve these objectives. MForesight hosted a series of roundtables in early 2018 to begin this conversation, attended by diverse stakeholders from business, government, and academia. These discussions generated a number of promising ideas to address the grand challenges that were identified at the roundtables. A summary of actionable next steps that the nation needs to take to overcome the grand challenges follows.

Invest in Translational R&D and Manufacturing Innovation

Restoring the ability to generate wealth from the billions invested in R&D should be a national priority. The innovation cycle that converts R&D results—new inventions and discoveries—into successful commercial products is working well in software, but has multiple breakdowns for manufactured hardware. Funding for the translational research needed to develop operational prototypes, demonstrate manufacturability, and identify viable markets is frequently unavailable so promising technologies languish in laboratories. Funding and expertise is needed to address the needs and ensure domestic production. This gap is so significant and the potential results so important that roundtable participants suggested creating **Translational Research Centers** (TRCs). TRCs would typically be independent non-profit corporations affiliated with a single or group of universities with strong industrial involvement. They would combine funding with expertise in product development, engineering, production, marketing, and other business functions needed to identify and nurture promising research results into commercial products and processes manufactured in this country. TRCs would provide skills that academic researchers usually do not have, help to lower the risk of commercialization and thereby attract private investment, and create a stronger pipeline from academic R&D to new products with positive impacts on national security and economic

87 The goal is to advance both Technology Readiness Levels (TRLs) and Manufacturing Readiness Levels (MRLs).

prosperity. Appendix A provides additional details on the TRC concept.

Mechanisms are also needed to ensure that needed advances in manufacturing technologies are developed and implemented domestically. **Advancing the Manufacturing Readiness Level** of a technology is often an essential step in reducing technical risk and attracting the private investment needed for full-scale manufacturing. In some cases, new manufacturing processes are necessary; in others, known processes can be used to demonstrate manufacturability, quality, and cost effectiveness. Several Manufacturing USA institutes are developing technologies for production of power electronics, functional fabrics, flexible electronics, and other critical technologies. Similar opportunities will continue to emerge from NSF-funded Engineering Research Centers, national laboratories, and even private companies working in areas such as autonomous vehicle sensors and control systems, advanced energy storage, and 5G equipment. In all cases, investments in applied engineering and manufacturing process research, coordinated with the translational research done at the TRCs would increase the likelihood of creating long-term competitive advantages that are difficult to copy.

One approach to advancing MRLs proposed by the roundtable participants would be to **establish additional Manufacturing USA institutes.** Existing Manufacturing USA institutes are mostly focused on specific technologies, such as flexible electronics, robotics, and bio-pharmaceuticals. **Additional institutes would be useful to rebuild foundational manufacturing know-how** while, at the same time, advancing capabilities in platform manufacturing technologies for multi-industry applications. Areas to be addressed would include metal forming, joining methods and technologies, laser processing, and process technologies for cost-effective low-volume manufacturing, to name a few. These institutes would focus on continuous improvement of widely used manufacturing processes, and work closely with domestic equipment makers to speed technology dissemination to commercial industry.

Another approach would be to **launch special competitions.** Competitions have proven to be an effective method for generating creative solutions to technical challenges. Competitions have been used by government agencies such as DARPA, non-profits such as XPRIZE, and private manufacturers such as General Motors to generate creative ideas from a broad audience. The goal would be to engage researchers to focus on manufacturing challenges in order to create and establish unique manufacturing capabilities that will provide U.S. producers with competitive advantages in multiple industries. One approach would be to assemble a group of experts who would identify a number of "moonshots"—important, long-term national objectives requiring advances in manufacturing technology and product innovation.

Encourage Pilot Production and Scale-up

To restore domestic production and overall leadership in emerging industries, America needs to invest in advancing manufacturing technologies, increasing pilot production, and scaling up to viable commercial volume. The necessary investment is largely the responsibility of the private sector, which means that national policies at all levels of government must remain conducive to profitable domestic production. Without addressing specific economic policies, which was beyond the scope of the roundtable discussions, participants did identify opportunities to take advantage of emerging technology developments to regain domestic production capacity. For example:

- Semiconductor packaging has long been done offshore, a legacy of the labor requirements of packaging processes. Packaging is now automated with little labor content. Furthermore, new technologies in which multiple chips are packaged together as System-in-Package (SiP) have created an opportunity to re-establish packaging in the United States. Government procurement from domestic sources would speed that development.
- Pharmaceutical production is on the verge of dramatic change with the emergence of continuous manufacturing methods for powder-based pharmaceuticals. The technology provides a mechanism to ensure cost-competitive domestic production of pharmaceuticals.[88]

In these and similar cases, government, especially defense, procurement contracts have proven to be an effective tool. Because it is important to create demand, not just supply, for advanced technologies manufactured in this country, the United States should **leverage government procurement** to create lead markets for new products and technologies. The federal government has a history of building strong national industries through a combination of R&D and procurement contracts. Aviation and the internet are obvious examples. Government purchase orders are an effective tool for companies to raise needed capital, both investments and loans, to initiate pilot or scale production domestically. Assured markets of sufficient scale are essential to successful product launches and will incentivize private investment necessary to create needed manufacturing technologies and production facilities.

Although procurement contracts are an effective tool, they are not a universal solution. New mechanisms are needed to ensure that domestic resources are available to scale production here, rather than contracting manufacturing to Asian producers, especially for high-value, high-technology products. An opportunity exists to **form geographically dispersed manufacturing investment funds.** These funds could be organized as public-private partnerships, or build on existing state government funds, to ensure that hardware start-ups have a reliable source of investment capital and can scale production in this country. The lessons learned from existing state-level programs should be applied to ensure effective use of the resources.

Empower Small and Medium-Sized Manufacturers

Small and medium-sized manufacturers are the backbone of U.S. manufacturing.[89] SMMs are important anchors in their communities and critical to systems integrators. Most do not entertain offshoring strategies, yet increasingly compete with Asian producers. If U.S. manufacturing is to regain international competitiveness and take advantage of the opportunities presented by smart manufacturing technologies, SMMs will need to implement those technologies broadly and effectively. Roundtable participants recognized that multiple federal and state programs provide support of various types to SMMs, but they also suggested that more could be done to accelerate their adoption of smart manufacturing technologies, and to ensure that SMMs have access to technical skills and expertise they will need to be effective in the future. Suggestions to do that include:

88 Koons, C. (2018, April 11). Why we may lose generic drugs. *Bloomberg.* Retrieved from https://www.bloomberg.com/news/articles/2018-04-11/are-drug-prices-too-low

89 SMMs have 500 employees or less and comprise over 98% of U.S. manufacturing firms and over 89% of establishments. United States Census Bureau. (2018). *2015 SUSB Annual Data Tables by Establishment Industry.* Retrieved from https://www.census.gov/data/tables/2015/econ/susb/2015-susb-annual.html

A. Provide loan guarantees and technical assistance to accelerate the pace of modernization of SMMs including capital equipment and implementation of smart manufacturing technologies. In partnership with states and existing federal programs, such as those at the Small Business Administration, this program would incentivize the purchase of domestically manufactured equipment and technologies to help rebuild the domestic machine tool industry, and to ensure that critical advanced manufacturing equipment and components are made and deployed domestically.[90]

B. Fund nation-wide educational and informational programs to ensure that SMMs are aware of government procurement opportunities, emerging domestic and export market opportunities, new technologies, and the capabilities of foreign competitors to facilitate better matching of domestic demand with domestic production. Working in collaboration with the Manufacturing Extension Partnership, such programs could accelerate the re-emergence of diverse, geographically distributed industrial ecosystems.

C. Create a program of industry fellowships to pay recent engineering and management retirees to work with the next generation of manufacturing start-ups, as well as business incubators and technology accelerators. Recent retirees are an underused resource, and in some cases, they are moving abroad to coach foreign competitors. A viable domestic alternative to capture such expertise before it is lost is essential to rebuilding the manufacturing knowledge base.

D. Develop simple technology licensing agreements to facilitate and encourage technology transfer and joint technology development between universities and industry, especially SMMs. Licensing technologies from universities can be overly complex and expensive, limiting the number of potential licensees. Useful models have been developed by some universities, which should be propagated nation-wide.

Grow Domestic Engineering and Technical Talent

Especially, though not exclusively, in academic R&D, the nation is dependent on foreign nationals in many scientific and engineering fields. In 2015, foreign students received 56 percent of engineering doctorates, 53 percent in mathematics and computer science, and 44 percent in physics.[91] Many factors affect domestic and foreign students' decisions to pursue graduate degrees, including available financial support, strength of the job market, and calculations of future earning power. The United States is fortunate to attract foreign students in large numbers, but would be remiss in continuing to depend on them, especially because foreign students are increasingly returning to their home countries upon graduation.

Other skills essential to restoring the nation's Industrial Commons and to effective implementation of smart manufacturing technologies require technical training, both broad-based and specialized. Accessing needed skills is frequently listed as the top challenge facing manufacturers in most industries today. Many community colleges have developed training programs targeting specific manufacturing skill requirements, often in concert with local manufacturers, but more needs to be done.

90 Such a program could incentivize foreign manufacturing equipment companies to create or increase U.S. production capacity.
91 National Science Foundation. (2018). *Science & Engineering Indicators 2018*. Retrieved from https://www.nsf.gov/statistics/2018/nsb20181/

Because human resource issues are so complex, the roundtable participants did not attempt to suggest comprehensive solutions, but they did identify a few initiatives that could improve the current situation in engineering and technical talent. For instance, recognizing the current dependence on foreign students in many graduate programs in STEM fields, roundtable participants suggested steps to increase the supply of domestic graduate students. One way would be to significantly **increase the availability of graduate fellowships for qualified domestic students.** This simple, cost-effective step would help to limit inadvertent transfer of R&D results offshore, rebuild the supply of researchers available to domestic industry, and, importantly, increase the number of highly trained scientists and engineers who can work in defense industries.

Roundtable discussions also addressed the need for a strong pipeline of technical talent available to SMMs. To cope with a growing wave of retirees and a shortage of young people with appropriate skills, an increasing number of manufacturing companies are creating apprentice programs and working with local technical schools to create custom training programs, often with employment guaranteed to successful graduates. Yet potential students usually are not aware of them. A useful step would be to **create a national registry of apprenticeship and other industrial training programs** with the ability to match available programs with high school and college students and veterans seeking opportunities with SMMs, along with funding support for trainees. A national registry of such programs would better match student interest with employment opportunities and contribute to restoring the Industrial Commons.

To complement apprenticeship programs, roundtable participants also identified the need for a renewed national focus on **educating engineering technicians with emphasis on applied engineering skills.** A frequent complaint among manufacturers is that engineering graduates have insufficient practical skills to make an immediate contribution to factory operations, while still having significant salary expectations. Mobilizing the broad higher education community to educate more engineering technicians would meet a growing need and likely attract more students and veterans to applied engineering. This program could be a three-year polytechnic degree, could provide scholarships to pursue cooperative education programs at SMMs, could be a collaboration between trade schools and engineering colleges, or could be other creative paths that supplement a traditional undergraduate engineering curriculum.

IMPLEMENTATION STRATEGIES

All of these suggestions emerging from MForesight's roundtables address clearly defined components of the grand challenges facing U.S. manufacturing. Ideally, the United States will, at some point in the future, create a national manufacturing strategy as international competitor nations have done. These ideas should be part of such a strategy, ideally implemented in a coordinated way with a **single point of focus** to orchestrate the required funding streams and to maintain strategic program management.

Currently, multiple offices and agencies at both the federal and state levels of government, as well as a few private non-profit organizations and public-private partnerships, support technology development, but there is no single point of focus to provide national strategic direction, or to provide the cross-cutting focus on manufacturing and systems engineering needed to bridge the hardware innovation gap. **Manufacturing cuts across multiple disciplines and technologies so it is therefore all the more compelling to have a single focal point for engineering and manufacturing research and innovation.** The needed point of focus could take one of several possible forms—a publicly funded non-profit organization, a federal-state-industry partnership, or a federal office or agency. Its mission would be to fill the existing gaps in the national innovation cycle by providing funding for translational research to advance TRLs and MRLs, to help rebuild the Industrial Commons through strategic investments in workforce development, and to support hardware start-ups with investments, loans, expertise, and networking to encourage production scale-up this country.

Manufacturing *really* matters. Research and invention alone are not enough to ensure national prosperity. To reap the full rewards of rapid technological advances, the nation must be able to manufacture products. Because of a confluence of economic and technological forces, the United States now has an opportunity to rebuild its manufacturing base and restore its global competitiveness. **But another report won't help.** Bold steps commensurate with the scale and importance of the objectives are absolutely necessary. The roundtable participants proposed a few implementation options, including creating a national innovation initiative, establishing a national manufacturing innovation foundation, and establishing a manufacturing program within each of the federal S&T agencies. They fully expect policymakers to convene and make decisions on how best to implement the critical steps identified in the previous section. **A piecemeal approach, addressing one or two critical steps but not all, will not help.** Other nations are not standing still. The onus is on us.

Appendix A: Translational Research Centers

One of the ideas discussed in depth at MForesight's manufacturing roundtables is to create a number of Translational Research Centers (TRCs). These would be designed to address market failures, fill gaps in the innovation ecosystem, ensure superior defense technology and capacity, and regain a vibrant, competitive industrial base.

Mission

Translational Research Centers will provide funding for product development to fill the gap between academic researchers with a potential hardware product or manufacturing process technology and domestic production. Employing professional engineers and managers experienced in new product introductions, the TRC will guide and fund research needed to translate laboratory results to testable beta prototypes and facilitate connections with domestic manufacturers to scale domestic production. Filling this gap will reduce the technical and market risk, attract private sector investment, retain and scale commercial production in the United States, and thereby multiply and accelerate the economic benefits from federal investments in academic research. TRCs serve as a means to translate promising technologies resulting from basic research conducted at affiliated universities into (hardware) products or processes for scaled production in the United States.

Background

- Federal R&D obligations in 2016 were $140 billion. Federal R&D spending at universities was nearly $40 billion. Of that, approximately $18 billion was spent on life sciences by NIH, and roughly $12 billion was spent on engineering research across all agencies. In 2016 alone, universities spent nearly $550 million on equipment for engineering research.[92]
- Almost no government funding is currently available for the translational research needed to create viable hardware prototypes or to scale production, leaving many discoveries and inventions languishing in the laboratory or, increasingly, commercialized outside the United States.
- Venture capitalists invest very little in hardware commercialization.
- A small federal investment in translational research would ensure greater domestic economic impact from R&D funding, dramatically increasing the return to federal R&D spending.

Existing Commercialization Process

- Commercializing results of university research is dependent on licensing, but results are rarely developed sufficiently to demonstrate the value to a potential licensee.
- University spin-off companies, start-ups established to commercialize university research, frequently lack rigorous product development skills and have difficulty raising sufficient capital

92 National Science Foundation. (2018). *Science & Engineering Indicators 2018.* Retrieved from https://www.nsf.gov/statistics/2018/nsb20181/

to mature hardware technologies as well as to develop (or contract) needed manufacturing processes.

- Venture capitalists (VCs) limit investments in hardware start-ups because the risk profile is multifaceted and hardware overall is more risky, time consuming, and expensive than software. VCs invest less than 5 percent in hardware start-ups. Some states and universities have created small VC funds for university start-ups, but even these favor information technology and healthcare start-ups.

- The result is that potentially promising research results do not receive additional effort to create commercial hardware products because funds are not available. The national wealth that could be created from research by introducing new products and technologies is foregone or captured by foreign competitors. Simply creating knowledge without a means to create national wealth from that knowledge is not sustainable.

Translational Research Centers

- TRCs would fill a gap in the current innovation ecosystem by funding translational research and facilitating scale-up needed to spur commercialization of the most promising results from academic R&D. TRCs would fund experienced product development teams working with start-ups to develop commercially viable hardware prototypes, perform validation testing to demonstrate the value proposition, and work with U.S. manufacturers, typically small and medium-sized manufacturers, to identify a path to full-scale production in the United States.

- TRCs would work with a single university or multiple regional universities to identify promising hardware technologies emerging from research results.

- TRCs could take multiple possible legal forms. Although TRCs are affiliated with universities, they should be independent from universities, although they could be part of university research corporations. Most likely, they would be independent non-profit corporations. Each TRC would establish relationships with affiliated universities to allow sharing of license fees and royalties from successful products and/or processes.

- Regardless of legal form, the overhead rate on federal funds would be limited to a maximum of 15 percent.

- The TRC would employ professional engineering and management staff to serve as systems engineers, project managers, market researchers, and private sector liaisons. Experienced product development teams would apply rigorous processes to specify, design, build and test hardware products/processes in the context of anticipated use cases to ensure timely results and high levels of domestic commercialization.

- Any technologies funded through TRCs would be subject to simplified licensing agreements to encourage licensing by SMMs. Licensing of resulting products must be restricted to U.S. production facilities only.

- Commercial production or use of resulting process technologies would be strictly limited to the United States to increase domestic manufacturing output and exports.

Funding

- An initial pilot program would fund 10 TRCs around the country, selected based on competitive proposals.
- Each TRC would be funded at up to $10 million annually, for an initial 3-year award. The amount of funding provided would be commensurate with the associated universities' federal research funding, up to 3 percent of basic research funds.
- Continued or increased funding would depend on performance as determined by an assessment scorecard.

Assessment Scorecard

The intent of this initiative is to mature promising results from the basic research conducted at affiliated universities. TRCs, in collaboration with their affiliated universities, are at liberty to choose the technology projects to be pursued. The results reported in the scorecard will be used to assess the effectiveness of the affiliated university in transitioning promising research into domestically scalable products/processes in the marketplace. Each TRC will be scored based on a series of leading and lagging metrics indicative of positive impact on the U.S. economy. Metrics would include:

- Number of private sector jobs created (maximum score = 20)
- Amount of private sector investment (does not include state or federal funds or university funds; does not include "commitments") (maximum score = 20)
- Number of start-ups successfully scaling profitable production (maximum score = 10)
- Number of U.S.-based SMMs engaged in the production, technology transfer, and/or development process (maximum score = 10)
- Number of technologies exceeding Technology Readiness Levels (TRL) 6 and Manufacturing Readiness Level (MRL) 5, according to standard TRL and MRL assessments used by the Department of Defense (maximum score = 10)

Continued funding would be based on the annual score achieved:

- Award amount may be increased with a score above 55.
- Continued funding for 2 years after the initial 3 year award requires a score above 40.
- Funding would terminate at the end of the fifth year if the score is below 45.
- Funding would be extended at the end of the fifth year for an additional 3 years if the score is at least 55.
- The TRC scorecard will be used in the evaluation of all future proposals submitted by the participating universities.

Proposal Evaluation Criteria

The initial ten TRCs should be selected based on a Request for Proposals. Multiple legal structures, formal relationships with universities, industry and technology foci, non-federal funding sources and partnerships, and other characteristics should be encouraged to maximize the lessons from the pilot program, though the same assessment scorecard must be used for all TRCs. The initial ten TRCs should focus on universities, though subsequent centers could work with other recipients of federal R&D funding such as non-profit research institutions and national laboratories. Achieving the desired impact—real, measurable economic benefit to the United States—will be the ultimate determinant of success. Proposal evaluation criteria should be based on the likelihood that proposers can achieve that goal.

Appendix B: Roundtable Participants

Boston, MA (January 18, 2018)

1. Dean Bartles, Director of the John Olson Advanced Manufacturing Center - University of New Hampshire
2. Bill Bonvillian, Lecturer - MIT
3. Sam Feller, Founder - Awkward Engineer
4. John Hart, Associate Professor - MIT
5. Christian Hoepfner, Executive Director - Fraunhofer USA Center for Sustainable Energy Systems CSE
6. Micaelah Morrill, Director of the Manufacturing Initiative & Acting Executive Director - Greentown Labs
7. Ira Moskowitz, Director of Advanced Manufacturing Programs - Massachusetts Technology Collaborative
8. Venky Narayanamurti, Benjamin Peirce Professor of Technology and Public Policy at the Harvard School of Engineering and Applied Sciences - Harvard University
9. Dave Rapaport, Head of Research & Collaboration Management US - Siemens Corporate Technology
10. Liz Reynolds, Executive Director MIT Industrial Performance Center
11. Peter Russo, Director of Growth & Innovation - MassMEP
12. Matt Sweitzer, Manufacturing Fellow - Greentown Labs
13. Jim Watkins, Professor of Polymer Science and Engineering - University of Massachusetts, Amherst & Director - Center for Hierarchical Manufacturing
14. Johanna Wolfson, Principal - PRIME Impact Fund

Washington, DC (January 22, 2018)

1. Rob Atkinson, President - Information Technology and Innovation Foundation
2. Norman Augustine, CEO (Ret.) - Lockheed Martin & Former Under Secretary of the Army
3. Kurt Bettenhausen, Senior Vice President - Siemens Corporate Technology USA
4. Robyn Boerstling, Vice President, Infrastructure, Innovation and Human Resources Policy - National Association of Manufacturers
5. Walter Copan, Under Secretary of Commerce for Standards and Technology and NIST Director - NIST
6. Ron Hira, Professor of Public Policy - Howard University & Research Associate - Economic Policy Institute
7. Paul Kern, Senior Counselor - Cohen Group
8. Mark Mills, Senior Fellow - Manhattan Institute
9. Shirish Pareek, CEO - Hydraulex Global
10. Willy Shih, Robert and Jane Cizik Professor of Management Practice in Business Administration - Harvard Business School

11. Jeff Wilcox, Vice President for Engineering and Program Operations - Lockheed Martin
12. Chad Moutray, Chief Economist - National Association of Manufacturers
13. Andrew Bicos, ASME Legislative Fellow - Office of U.S. Congressman Reed
14. Pramod Khargonekar, Vice Chancellor for Research and Distinguished Professor of Electrical Engineering and Computer Science - University of California, Irvine
15. Mike Russo, Director & Corporate Lead of U.S. Government Affairs - GLOBALFOUNDRIES

Austin, TX (February 23, 2018)

1. Joe Beaman, Professor & Earnest F. Gloyna Regents Chair in Engineering - University of Texas at Austin
2. Roger Bonnecaze, William and Bettye Nowlin Chair in Chemical Engineering & Co-Director of NASCENT - University of Texas at Austin
3. Larry Dunn, Assistant Director of Industry and Innovation Programs at NASCENT - University of Texas at Austin
4. Brian Korgel, Professor, Edward S. Hyman Endowed Chair in Engineering - University of Texas at Austin & Director of Industry/University Cooperative Research Center on Next Generation Photovoltaics
5. Dwayne LaBrake, President and Chief Executive Officer - Canon Nanotechnologies
6. Ed Latson, Executive Director - ARMA—Austin Regional Manufacturers Association
7. Ken Pfeiffer, Vice President of Engineering - Superconductor Technologies Inc.
8. Bill Rafferty, Manager of Process Improvement Engineering - Southwest Research Institute & South Central Regional Director - Texas Manufacturing Assistance Center (TMAC)
9. John Randall, President - Zyvex Labs, Dallas
10. S.V. Sreenivasan, Prof. & Co-Director of the NASCENT Center - University of Texas at Austin
11. Krishna Srinivasan, Founding General Partner - LiveOak Ventures
12. Bill Stueve, President - Atonometrics
13. Sarah Holloway, District Field Director - Office of Congressman Michael T. McCaul (TX-10)

San Jose, CA (March 8, 2018)

1. Bob Brakeman, Independent Consultant
2. Megan Brewster, Vice President of Advanced Manufacturing - Launch Forth
3. Glenn Daehn, Fontana Professor of Materials Science Engineering & Director for Manufacturing, Institute for Materials Research - The Ohio State University
4. Cyril Ebersweiler, General Partner, SOSV & Managing Director, HAX
5. Mauricio Futran, Vice President, Process Science and Advanced Analytics - Johnson & Johnson
6. Jim Myrick, Entrepreneur in Residence - Flextronics
7. Shirish Pareek, CEO - Hydraulex Global
8. David Parrillo, Global Research & Development Director for DowDuPont Packaging and Specialty Plastics - The Dow Chemical Company
9. Sean Randolph, Senior Director - Bay Area Council Economic Institute
10. Greg Reichow, Partner - Eclipse Ventures
11. Mike Russo, Director & Corporate Lead of U.S. Government Affairs - GLOBALFOUNDRIES

12. Randy Schiestl, Vice President, R&D, Global Technology & Services - Boston Scientific Corporation
13. Diego Tamburini, Principal Industry Lead for Azure Manufacturing - Microsoft
14. Malcolm Thompson, Executive Director - NextFlex
15. David Vasko, Director of Advanced Technology - Rockwell Automation
16. David Wahl, Senior Vice President and General Manager - Jabil

Raleigh, NC (March 14, 2018)

1. Paul Cohen, Woolard Distinguished Professor, Fitts Department of Industrial and Systems Engineering - North Carolina State University
2. Steve Ellis, CEO - Automated Solutions
3. John Hardin, Executive Director - North Carolina Board of Science, Technology & Innovation
4. Nick Justice, Executive Director - PowerAmerica Institute
5. Russell King, Foscue Distinguished Professor & Co-Director of the Center for Additive Manufacturing and Logistics - North Carolina State University
6. John Loyack, Vice President of Global Business Services - Economic Development Partnership of North Carolina
7. Mike Mazzola, Director of the Energy Production and Infrastructure Center - University of North Carolina at Charlotte
8. Steve McManus, Innovation Manager - RTI
9. Phil Mintz, Executive Director - NC State Industry Expansion Solutions & Director - North Carolina MEP
10. Zack Oliver, Economist - RTI
11. Scott Smith, Professor & Department Chair, Mechanical Engineering and Engineering Science - University of North Carolina at Charlotte
12. Binil Starly, Associate Professor, Industrial and Systems Engineering - North Carolina State University
13. Bob Wilhelm, Vice Chancellor for Research and Economic Development - University of North Carolina at Charlotte
14. Fiona Baxter, Associate Executive Director - NC State Industry Expansion Solutions

Indianapolis, IN (March 21, 2018)

1. Keith Belton, Director of the Manufacturing Policy Initiative - Indiana University Bloomington
2. Andrew Berger, Senior Vice President of Governmental Affairs - Indiana Manufacturers Association
3. Matt Conrad, Executive Director, Indiana Automotive Council - Conexus Indiana
4. Claudia Cummings, Vice President, Strategic Development - Conexus Indiana
5. Jennifer Hagan-Dier, Manufacturing Extension Partnership Director, Center for Industrial Services - University of Tennessee
6. Ned Hill, Professor of Public Administration and City & Regional Planning - The Ohio State University
7. Steve Jones, Professor of Finance, Kelly School of Business - IUPUI
8. Razi Nalim, Associate Dean for Research, School of Engineering and Technology - IUPUI

9. Clayton Nicholas, Industry Research Development Specialist, School of Engineering and Technology - IUPUI
10. Ray Niehaus, Managing Director of Innovation and Technology - Mid-America Science Park
11. Dave Roberts, Chief Innovation Officer - Indiana Economic Development Corporation
12. Dave Snow, Director - Indiana MEP
13. Stan Woszczynski, Vice President, Chief Manufacturing Officer - Cummins, Inc.
14. James Ruble, Advanced Composites Outreach Consultant, Center for Industrial Services - University of Tennessee
15. Tim Frazier, Executive Director of Advanced Engineering - Cummins, Inc.

Dearborn, MI (March 29, 2018)

1. Carla Bailo, President and CEO - Center for Automotive Research
2. Timothy Bartik, Senior Economist - Upjohn Institute
3. Mike Coast, President - Michigan Manufacturing Technology Center
4. Chris Conrardy, Executive Director - LIFT & Chief Technology Officer and Vice President for Strategic Initiatives - EWI
5. Chuck Hadden, President & CEO, Michigan Manufacturers Association
6. Fred Keller, Founder and Chair, Cascade Engineering
7. Tom Kelly, Executive Director and CEO, Automation Alley
8. Jeff Krause, Executive Director and CEO, SME
9. Andrew McColm, Managing Director, Venture Creation - Spartan Innovations
10. Mark Montone, Director of Sales and Marketing North America - Lacks Trim Systems LLC
11. David Ollila, President and Chief Innovation Officer - Skypoint Ventures
12. Kirk Roys, Director of Global Technical Services - Steelcase
13. Ryan Sekol, Senior Researcher, Manufacturing Systems Research - General Motors Global Research and Development
14. Kelly Sexton, Associate Vice President for Research - Technology Transfer and Innovation Partnerships - University of Michigan
15. Dan Slane, Owner - The Slane Company
16. Alan Taub, Chief Technical Officer - LIFT

Other Contributors

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4. Charles L. Cooney, Robert T. Haslam (1911) Professor of Chemical Engineering, Emeritus, and Faculty Director, Emeritus, Deshpande Center for Technological Innovation, MIT
5. Lawrence D. Burns, Vice President (retired), R&D, General Motors
6. Pat McGibbon, Vice President, Association for Manufacturing Technology
7. Kirsten Rieth, Senior Innovation Advisor, RTI
8. Madhav Acharya, Technology-to-Market Advisor, ARPA-E
9. Charles Zukoski. Provost, University at Buffalo
10. Sue Babinec, Senior Commercialization Advisor, ARPA-E, Dept. of Energy

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