Building the Infrastructure for Innovation:

Three Lessons for Implementing the CHIPS and Science Act

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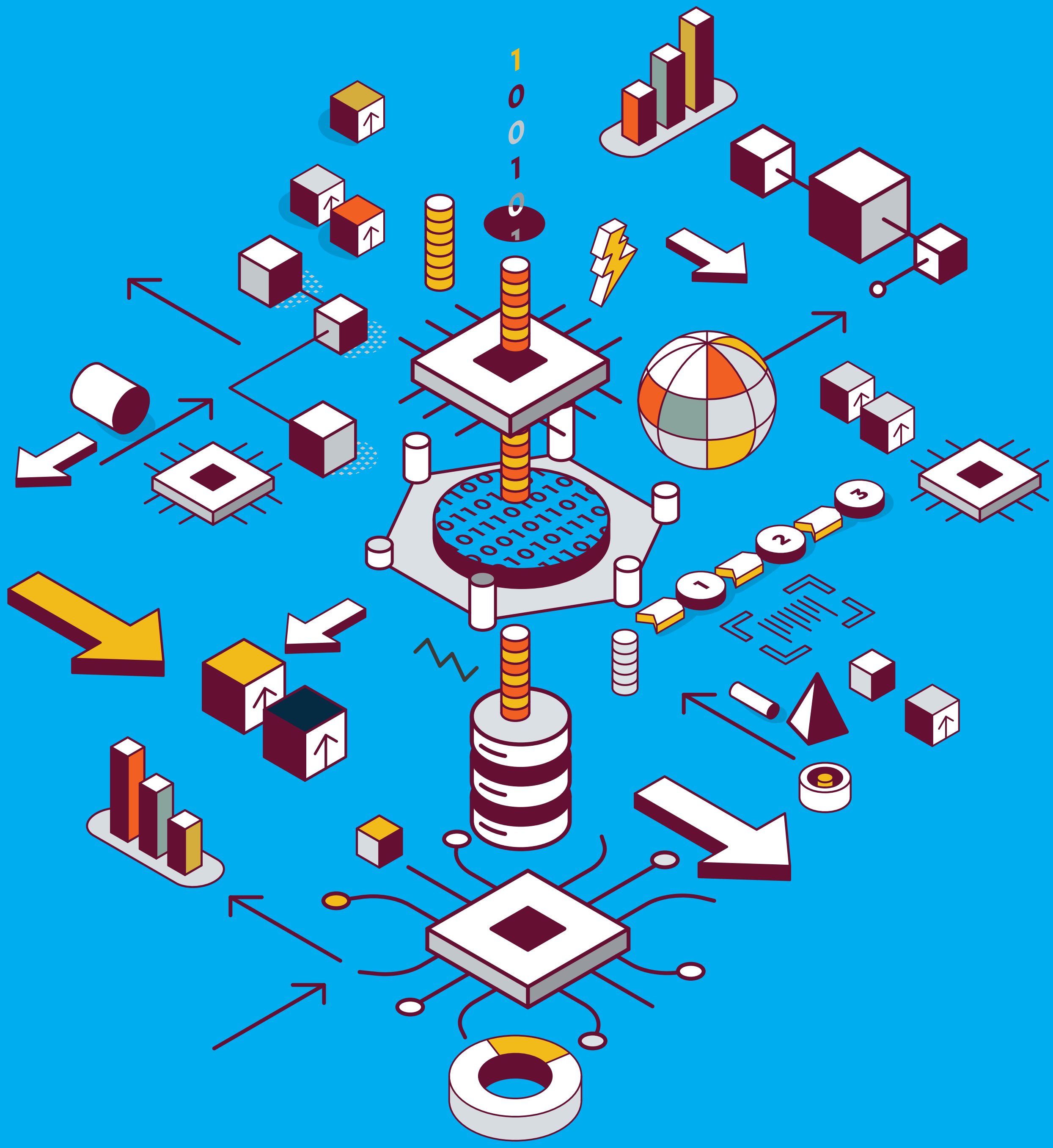


September 2023

Acknowledgements

We are thankful to the Taiwan Semiconductor Manufacturing Company for sponsoring research on the U.S. microelectronics ecosystem that contributed to this report. We are also grateful to Schmidt Futures and the Siegel Family Endowment for supporting research on U.S. manufacturing and the workforce that helped motivate the recommendations herein. We appreciate the time and insights from senior personnel at TSMC, as well as other leading companies in the U.S. microelectronics ecosystem, who were interviewed as part of this study and provided feedback on its contents. The research contributing to this study was conducted independently by the authors.

EXECUTIVE SUMMARY

A spotlight is on the U.S. semiconductor industry. After decades of decline, there is a wave of new investment from private industry and the federal government to jumpstart domestic chipmaking with the goal of making U.S. semiconductor production more cost competitive and technologically advanced. Whereas the United States did not have any chipmaking capacity at the most advanced nodes (<10nm) in 2019, TSMC (Taiwan) and Samsung (South Korea) have since launched greenfield foreign direct investment projects to establish new chip fabs at the 5nm node size that will enable the most advanced chips to be produced in the United States. Government and industry reports have underscored the potential for these investments to transform the U.S. economy. They highlight opportunities to rebuild domestic manufacturing capabilities, create high-wage jobs, and drive innovation in a sector with wide-reaching impact on the global economy.

There are three primary channels through which these investments can make an impact. For one, they can improve the productivity and technological capabilities of domestic semiconductor firms. They can also drive new domestic R&D that can generate innovative startup companies. And finally, foreign direct investment from firms like TSMC and Samsung can bring new knowledge and human capital to the domestic industry. In other contexts, foreign direct investment has led to spillover benefits, including increased productivity at domestic firms, higher wages among affected workers, and more regional innovation overall.

The three channels are linked: foreign direct investment has the potential to improve the competitiveness of domestic semiconductor firms and drive innovation in the ecosystem as a whole. The federal government's CHIPS and Science Act is designed to maximize the impact of new investments like these through each of these channels. The Commerce Department, charged with implementing the CHIPS and Science Act, has developed an ambitious vision that aims to seize these opportunities. It has three core elements: i) building regional clusters around advanced chip fabs, ii) scaling a skilled and diverse workforce, and iii) strengthening U.S. technology leadership in the industry.

The CHIPS and Science Act provides an outline for what the government hopes to achieve, but the details of how to achieve it are waiting to be filled in. Past research on industrial policy and current U.S. manufacturing data identify obstacles that could stand in the way of success. But these obstacles are avoidable. This report provides three lessons that can guide the implementation of public investments and the structure of public-private partnerships to build on current momentum and avoid past mistakes.

1. REGIONAL CLUSTERS

Government support for regional clusters should help scale existing, promising industry linkages – not engineer new clusters from scratch. There is no guarantee that regional clustering around chip fabs will occur spontaneously. Data on regional industry concentration show that clustering around current U.S. chip fabs has been inconsistent. Market forces have supported the concentration of materials suppliers around some fabs and equipment manufacturers around others (see Figure 3). Moreover, previous government efforts to engineer industrial clusters have a mixed track record of success. Where government interventions have succeeded at supporting regional clustering, government has served as a *convener* of promising public-private cooperation and a *scout* for R&D partnerships that can scale.

2. WORKFORCE DEVELOPMENT

There are multiple semiconductor workforces that will require tailored workforce development investments. Recent evidence shows the promise of sector partnership models that could help scale the availability of semiconductor technicians through partnerships between industry consortia, training organizations, and non-profits that help workers transition into new careers. Although engineering and technician jobs at chip fabs are high-paying, advanced manufacturing jobs, these are not the only – or even the most numerous – jobs in the semiconductor ecosystem (see Figure 4). Equipment and chemical manufacturers that operate lower in the semiconductor supply chain face a persistent labor shortage in U.S. manufacturing that has coincided with rising turnover. For technical semiconductor roles, R&D partnerships with universities can double as workforce development. But support for the wider manufacturing workforce will require investments in productivity improvements that raise the wages and attractiveness of American factory jobs (and the price competitiveness of U.S. semiconductor production).

3. INNOVATION AND THE LONG TAIL

Companies and startups should have a seat at the table to participate in new R&D consortia. New investments in semiconductor R&D through the National Semiconductor Technology Center and new proposed Manufacturing USA Institutes dedicated to semiconductor-related technologies have the promise to drive important advances along Moore's Law and generate innovations in packaging, materials, design, and unanticipated domains that move the industry forward. These investments can also stimulate growth in an area of innovation that has stagnated in recent decades (see Figure 5). However, these initiatives can learn from past challenges at SEMATECH – a predecessor to NSTC – and other Manufacturing USA Institutes. These efforts have struggled to engage small and medium enterprises, as well as startups, in their large-scale research efforts due to concerns around IP sharing and gaps in resources between large and small firms. Despite the substantial obstacles to new business formation in the semiconductor industry (and the long-term decline of U.S. manufacturing startups), there is still opportunity for new companies to help motivate innovation in the industry.

Together, these lessons begin to provide a roadmap for how the implementation of the CHIPS and Science Act – and the establishment of regional semiconductor ecosystems around chip fabs – can build an infrastructure of innovation that delivers widespread economic benefits. The scale of the current investment in industrial policy is unprecedented, but the tactics have been tried and studied. Learning from past evidence can help policymakers and industry leaders seize this moment of opportunity.

INTRODUCTION: FROM SILICON VALLEY TO GLOBAL ECOSYSTEM

In early 1971, the trade journal *Electronic News* published a three-part series titled "Silicon Valley, USA." It traced the rapid growth of the semiconductor industry in California's Bay Area, coining a nickname that would come to be synonymous with rapid innovation and economic growth. In fifteen years, Silicon Valley went from having one semiconductor company – Shockley Transistor – to becoming the hub for a fast-growing industry with approximately two dozen companies including Intel and IBM.

Three forces seemed to drive innovation and growth during this early period. First, new companies had access to labs and infrastructure for research and development that the earliest semiconductor companies had begun to establish in the post-war period. Second, there was a common pool of talent – top researchers drawn from Bell Labs, Stanford, and elsewhere – excited to work in a growing industry. And third, the knowledge from one firm quickly spilled over to another as top employees at some semiconductor companies would spin off new startups ready to compete. The 1971 series notes the "tightlyknit group" within the industry that enabled an ongoing exchange of ideas: "Despite their fierce competition during business hours, away from the office they remain the greatest friends."[i]

The shared infrastructure, common pool of talent, and knowledge spillovers that fueled the growth of Silicon Valley became known as the core ingredients of industrial clusters. And they are ingredients that the CHIPS and Science Act is trying to re-establish today.

1. THE FOUNDRY REVOLUTION

Beginning in the 1980s and 1990s, the semiconductor industry underwent multiple transformations, and the focus of Silicon Valley shifted from hardware to software and the internet. Startups and new innovations continued to emerge from the region, but the semiconductor industry became more global. Several forces help explain the shift. For one, the United States economy in general shifted away from manufacturing and toward services during this period. The idea was that American companies could invent new technologies and have them produced elsewhere.

In the semiconductor industry, the innovation that made this shift possible was the emergence of the foundry model, pioneered by the Taiwan Semiconductor Manufacturing Company in the mid-1980s. The foundry model enabled one company to design chips, and another company (the foundry) to produce them. Each part of the value chain could specialize in its function. This was a sharp contrast from the integrated device manufacturer (IDM) model pioneered by Fairchild Semiconductor and Intel, where a single company would design and produce its own chips.

Taiwan, home to the foundry model, aimed to generate a high-growth industry cluster like Silicon Valley. A former Taiwanese Finance Minister, Kuo-Ting Li, studied the Silicon Valley model and even consulted with Stanford Dean Frederick Terman about how best to support semiconductor industry growth in Taiwan. Terman advised Li on the establishment of an industrial park near two of Taiwan's top universities. The Hsinchu Science Park, founded in the early 1980s, became home to TSMC as well as approximately 400 other companies in the semiconductor industry – manufacturing facilities as well as research labs and software development firms. The park attracted entrepreneurs and highly-educated semiconductor experts – many of whom had educational or professional experience abroad – back to Taiwan. But Taiwan was not the only new country to develop a cluster of new semiconductor companies.[ii]

What is the semiconductor ecosystem?

The industry group SEMI breaks semiconductor companies into four primary categories: materials, equipment, fab infrastructure and services, and devices.

Materials companies provide the wet chemicals, specialty gases, and other raw materials, such as silicon wafers, necessary to produce computer chips. Materials suppliers range from specialized producers of materials like photoresist exclusively for the semiconductor industry to bulk chemical manufacturers that sell to various industries with a range of specifications.

Equipment companies supply the machines that fabs and other factories use to measure, produce, test, package, and assemble devices. While many equipment suppliers in the industry are specialized, the machine tool manufacturers rely on suppliers of precision parts that are frequently not specialized. The same SME that might provide a part for a semiconductor instrument might also make similar parts for the aerospace or automotive industry.

Fabs manufacture computer chips and rely on services from facilities specialists expert in delivering gases or implementing anti-vibration protocols, as well as from software providers that have built electronic design automation (EDA) tools that enable device makers to design chips so that they are manufacturable in a fab. The high costs of building a fab include the services required to operate the fab at near-perfect efficiency, as well as to set up systems to supply raw materials, gases, chemicals, and equipment to sustain chip production.

Device in this construction refers to fabless firms like AMD and Nvidia that specialize in chip design for customers in the consumer electronics industry, as well as companies like Tesla that design some of their own chips for production at foundries. The device companies in this simplified categorization are typically the customer of the fab, whereas the fab is typically the customer of the materials and equipment suppliers.

The rise of a more globalized semiconductor industry enabled companies in Japan to specialize in substrate materials, China in printed circuit board materials, and the Netherlands in lithography equipment. Studies of the modern semiconductor industry frequently emphasize the global map of materials and equipment suppliers, device makers, and chip manufacturers. The semiconductor industry of 2023 relies on an interwoven network of global firms, competing and collaborating.

What connects companies across segments of the supply chain – equipment providers, software developers, and fabs – is their alignment behind a shared goal: innovating according to Moore's Law, which allowed for continuous improvements in chip performance and reductions in node size every several years. Although shrinking node size is not the only domain in which semiconductor companies innovate – they also collaborate around advanced packaging, new materials, and other R&D initiatives – this common endpoint has led to frequent knowledge sharing across firms and joint R&D projects. Whereas knowledge sharing in early Silicon Valley unfolded among neighboring competitors and former colleagues, the modern semiconductor ecosystem requires more formal global collaboration among established firms that rely on one another to achieve the next milestone along Moore's Law.

2. RE-INVESTING IN THE SEMICONDUCTOR INDUSTRY

In some ways, the globalization of semiconductor supply chains has been beneficial to American firms and consumers. It is likely that the foundry model has created more flexibility and a wider variety of choices for device makers in search of custom chips. The foundry model has also likely accelerated innovation through specialization, driving down costs for global consumers. Companies in the United States are important contributors to the global ecosystem, particularly in chip design and electronic design automation software.

But the United States has also recognized significant costs to losing its competitive edge in semiconductor manufacturing. The United States no longer has any chip fabs at the leading edge (that is, chips at the 5nm scale or below) and does not have domestic sources of critical materials or advanced packaging capabilities. This problem has come into sharp relief during repeated supply chain disruptions beginning in 2020, as well as geopolitical risks stemming from the war in Ukraine and tensions with China. But there have also been deeper challenges associated with the decline of U.S. manufacturing overall, including the hollowing out of middle-class jobs and the stagnation of industrial communities.

Perhaps most significantly, the loss of manufacturing capacity has been associated with reduced capacity to innovate. The idea is that the knowledge required to innovate in the design of a new product requires proximity to production. An engineer charged with designing a next generation vehicle or electronic device cannot make improvements in a vacuum. They must often spend time with those on or near the factory floor to understand where improvements are possible. They must coordinate closely with those involved in production. The offshoring of manufacturing capabilities formerly in the U.S. has severed connections between leading American research labs and the factory floor, weakening America's ability to lead in product innovation.

The confluence of short-term concerns during the pandemic, as well as persistent challenges associated with the decline of manufacturing has motivated a new wave of pro-manufacturing investment in the United States – and chip production has been a key target. Over the past two years, leading chip manufacturers have committed to hundreds of billions of dollars in new fab construction, and the federal government has allocated more than $75 billion as part of the CHIPS and Science Act, to support growth in the industry. This includes $39 billion in incentives for private firms (which can be leveraged to support up to $75 billion in loan guarantees), as well as $24 billion in investment tax credits. This funding aims to stop the erosion in the U.S. share of global semiconductor production which has fallen to 12%, and to enable domestic production of the most advanced chips. There is also up to $13 billion available for R&D initiatives including a National Semiconductor Technology Center and additional Manufacturing USA Institutes devoted to semiconductor technologies.[iii]

3. PATHS TO IMPACTS

The CHIPS and Science Act is designed to close the competitiveness gap between the United States and its foreign competitors. Currently, semiconductor production in the United States is more costly and less innovative than comparable manufacturing elsewhere in the world. Estimates from the Semiconductor Industry Association suggest that the ten-year costs of owning and operating a U.S. chip fab are 30% higher than operating a similar fab in Taiwan or South Korea and 50% higher than operating a fab in China. TSMC Founder Morris Chang estimates the cost of producing U.S. chips may be 50% higher than producing similar chips in Taiwan. Analysts attribute the cost gap to differences in government incentives, which the CHIPS Act directly addresses, as well as to differences in the productivity, skills, and wages of the workforce. Closing the gap, these arguments would suggest, will require more productive U.S. semiconductor manufacturing as well as more generous incentives.

The United States also does not currently have the capacity to manufacturing the most advanced logic chips, defined as leading-node chips <10nm. These chips are critical inputs for producing the most innovative devices including quantum and high-performance computing systems that can power artificial intelligence and machine learning applications. Whereas U.S.-based semiconductor firms can design and sell leading-node chips, and U.S.-based software providers can design EDA software for leading-node manufacturing processes, all leading-node chips are currently produced in Asia, with 92% produced in Taiwan and 8% produced in South Korea. Closing the gap in the most advanced semiconductor manufacturing capabilities is a two-pronged problem: the United States needs to build leading-node manufacturing capacity on the one hand, and it needs to support the innovation capacity so it can be first to stand up advanced manufacturing facilities at leading nodes in the future.

There are three channels through which the United States can boost the competitiveness of the domestic semiconductor industry and close these gaps.

The first is to invest in supporting innovation and skill development at domestic semiconductor manufacturers, equipment manufacturers, and material suppliers. New incentives and loan guarantees in the CHIPS and Science Act can provide capital for these firms to increase their investments in productivity-enhancing technologies and new R&D. The aim for this channel is to speed the productivity growth of U.S. firms so that they can catch up to – and eventually surpass – their global competitors.

A prominent example of private sector investments to boost domestic semiconductor firms is Intel's commitment to establishing a "mega-site" of semiconductor fabs and related R&D facilities near Columbus, Ohio. Although this site will attract suppliers and other companies in the semiconductor ecosystem to locate nearby, it is unclear how it will contribute to increased productivity and innovation among U.S. semiconductor firms to close the global competitiveness gap. Given the speed of innovation in the semiconductor industry – as well as the strong links between U.S. fabless semiconductor companies and global manufacturers – this cannot be the only channel through which the U.S. aims to close the competitiveness gap.

A second channel is to supercharge investment in domestic R&D – not only among incumbent U.S. firms, but also at U.S. universities and startup companies. A large focus of rebuilding the domestic ecosystem is to support the institutions where the United States currently has a comparative advantage. U.S. research universities and new, high-growth technology companies have a legacy of driving innovation in the microelectronics industry. The CHIPS and Science Act has emphasized the creation of a National Semiconductor Technology Center (NSTC), as well as new research funds for universities aiming to stimulate progress along this channel. However, university research has often lacked the advanced infrastructure (in terms of equipment and scale) required to innovate at the level and pace of industry. And given the capital required to innovate and compete in the semiconductor manufacturing value chain, generating startup companies from scratch will only be possible in narrow domains.

The third channel through which the United States can boost competitiveness is foreign direct investment. Foreign semiconductor manufacturers have a cost advantage and an innovation advantage over their U.S. counterparts. One path to closing the gap is for foreign industry leaders to invest in the United States, bringing the knowledge of advanced semiconductor production onshore. The foreign direct investment commitments from TSMC to build 5nm and 3nm fabs in Arizona – and from Samsung to build a 5nm fab in Texas – represent the onshoring of manufacturing know-how that did not previously exist in the United States.

The impact of foreign investments, previous studies suggest, often extends beyond the immediate factories that foreign companies commit to building. When foreign investors like TSMC and Samsung invest in a new process in the United States, they also attract suppliers from the countries where they are headquarters. Those suppliers bring additional knowledge and contribute to the formation of a local ecosystem. Multiple suppliers of TSMC and Samsung have already announced investments in Arizona and Texas, respectively, with TSMC predicting that 40 separate suppliers will locate near their Arizona campus.

The aggregate investment commitments of foreign direct investment from these two companies is substantial. Investments in their initial fabs total $39 billion with potential investments surpassing $200 billion. If they are completed, these foreign direct investment projects will likely be two of the largest foreign direct investment projects in U.S. history.[iv] To put these figures in context, the total foreign direct investment since 2014 in the United States to establish new companies and expand existing companies (excluding acquisitions of American companies) is $75 billion.

Foreign direct investment from innovative companies abroad has been associated with spillover benefits for the domestic economy. The theory is that when foreign companies invest in a domestic economy, they transfer new knowledge to domestic firms, improving the productivity and innovative capabilities of those firms. Foreign companies can also absorb knowledge from domestic companies, contributing positively to their performance.[v] Although the evidence on spillovers from FDI is mixed, there is evidence that spillovers can be more prominent in high-technology industries like semiconductors compared to lower-technology manufacturing sectors.[vi]

In the case of TSMC, the training of a skilled semiconductor workforce will be a critical avenue through which knowledge is transferred. TSMC has planned to train the workforce that will operate its fabs in Arizona at its advanced Taiwanese fabs. Arizona employees will spend months learning from experts on the manufacturing process at TSMC's comparable facilities near its headquarters. When TSMC starts production in Arizona, it also plans to bring its engineers and technicians from its Taiwanese fabs to lead the launch of the Arizona facilities. These investments in training across borders have the potential to increase knowledge spillovers to TSMC suppliers and U.S. firms, increasing the innovative capacity of the U.S. semiconductor ecosystem.

4. UNANSWERED QUESTIONS

With this surge of investment, this is clearly a moment of possibility for the U.S. semiconductor industry. But it remains unclear how the U.S. semiconductor industry will evolve over the next decade and beyond. What would a thriving U.S. semiconductor industry look like? How can government interventions and private investment contribute to success?

In February 2023, the federal government's new Chips Office released what they called a "vision for success" outlining what they see as key priorities for the industry. They emphasized three areas: 1) building regional clusters of suppliers, R&D, and production facilities anchored around large chip fabs, 2) training a "skilled and diverse" workforce to meet the industry's needs as it scales, and 3) driving innovation that makes the United States a technology leader in semiconductors.[vii]

Although this vision points in a promising direction, there are several unanswered questions. For example, past government efforts to support new clusters in the United States have largely fallen flat. What can the CHIPS Act implementation learn from past mistakes? There have also been concerns about the effectiveness of large-scale federal workforce development programs in the past. How can semiconductor-focused workforce development build on industry data and recent evidence? And university-based research in the United States has been criticized for falling behind industry. What models are there for promoting university-industry collaboration?

The purpose of this report is to examine how the three pillars of this vision might be realized – and what role government can play.

BALANCING THREE PERSPECTIVES

Over the past several years, as industry leaders and public officials debated the merits of the CHIPS Act, three competing perspectives emerged. Each sought to define what a thriving U.S. semiconductor ecosystem can (and should) achieve.

The first perspective emphasizes **economic security**. In this perspective, the presence of domestic capacity to produce chips – particularly the most advanced chips – is important because foreign sources of these chips are vulnerable to disruption. This economic security concern encompasses the interests of the U.S. military, which emphasizes national security concerns, as well as the interests of the U.S. consumer, which prioritizes reliable access to electronics.

Advanced semiconductors are widely recognized as a core ingredient in information technology innovation, including advances in artificial intelligence and quantum computing that are national security priorities. Moreover, the domestic capacity to produce chips (and supply chip producers with critical equipment and materials) is an insurance policy against future disruptions to the microelectronics supply chain. The implication of this vision for the U.S. semiconductor industry is that flexible capacity is more important than scale.

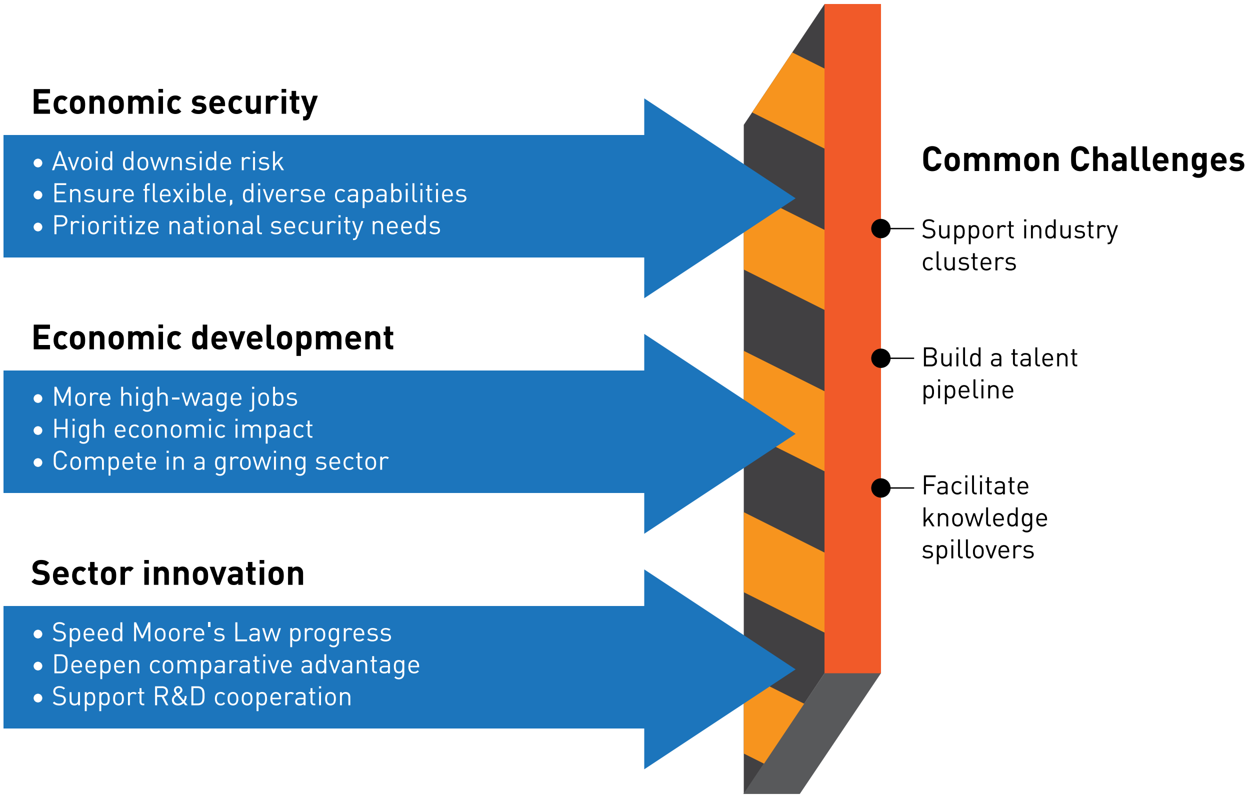
In this perspective, it is not critical that the United States becomes cost-competitive at producing chips or critical chemical inputs – only that the United States can produce a variety of chips in a pinch. National security interests have been the chief proponents of this perspective, articulating military interests in procuring advanced chips domestically (for which there is currently no capacity) rather than from abroad. The U.S. Defense Department experimented in the past with maintaining "trusted foundries" in the U.S. to provide a reliable source of chips, but these proved inadequate to obtaining access to cutting-edge technology. The military's need for a strong industrial base – as well as its demand for the most advanced technology – has helped motivate investment in the domestic semiconductor industry.

There are several open questions associated with the economic security perspective. The first is what capabilities are essential to have in the United States. The CHIPS and Science Act, along with announcements of new construction, emphasizes chip fabrication. But what material inputs for chip production are also necessary for the U.S. to be capable of supplying? Is high-purity single crystal silicon, which almost entirely comes from China, necessary to produce in the United States? Are specialty gases like Helium, which has supplies concentrated in Russia, a production priority? What is the cost premium to producing critical materials like these in the U.S. as opposed to importing them? This leads to a reality check: the United States will continue to rely on the global semiconductor ecosystem. The economic security goal then becomes: how can the United States reduce its vulnerabilities while continuing to benefit from access to global sources of innovation.

Investing in the semiconductor ecosystem with an emphasis on economic security comes with stark tradeoffs. For instance, the United States may have less comparative advantage in producing specialty gases than producing more advanced equipment or designing more advanced chips. Moreover, meeting economic security needs (without producing a sustained volume of chips or related materials) could result in fewer economic spillovers like increased jobs, exports, or innovation that helps fuel related industries.

A second perspective for investing in the U.S. semiconductor industry is driven by **economic development** goals. A thriving semiconductor industry, in this perspective, is one that creates high-wage jobs and generates benefits elsewhere in the economy. This

Figure 1
Three Paths for the U.S. Microelectronics Industry



is the lens through which state and local officials have approached the semiconductor industry as they offer tax incentives for chip manufacturers and their suppliers to construct new facilities in their jurisdictions. The success of investments in the semiconductor industry is linked to the jobs it creates and the indirect impact that it promises to have on the rest of a regional economy.

An economic development perspective is more likely to target areas of the semiconductor value chain where the United States has a comparative advantage in the market and can practically provide the talent, infrastructure, and knowledge to help a business grow. It is less likely to support investments that relieve supply chain constraints or help fill gaps in the domestic semiconductor ecosystem if they do not build on U.S. comparative advantage.

The open questions associated with these economic development goals center on the semiconductor workforce. How many long-term jobs will fab investments actually create given the changing skills and employment levels to run more advanced fabs? What training infrastructure will be required to meet firms' growth targets? What is the overlap in the demand for skills between chip manufacturers and their suppliers?

A third perspective, arising from industry leaders, emphasizes **innovation** in the semiconductor industry. Advocates for an innovation-focused approach emphasize investments that might propel Moore's Law forward, inspire new breakthroughs in advanced packaging and innovative materials, and accelerate progress in producing higher-quality chips at a more competitive cost. Since innovation in semiconductors is closely linked with innovations in other areas of computing, such as artificial intelligence, there are many stakeholders with an interest in continuing to drive innovation in the sector. And successful innovation could unlock growth opportunities in adjacent industries.

But innovation in the semiconductor industry is a global process. The best suppliers of material inputs come from multiple continents, as does the most advanced equipment. While it makes sense to diversify supply to some extent, this perspective emphasizes that the semiconductor industry should avoid duplication for duplication's sake. While the U.S. may be able to produce advanced chips onshore, retaining or slightly increasing its share of the world chipmaking market, and improving supply chain resiliency, it will remain dependent on international producers.

Essential to progress in the semiconductor industry, this perspective argues, is cooperation across firms and across borders. Each wave of progress in chip technology has required extensive coordination between equipment manufacturers like ASML, chip design firms like AMD and Nvidia, chip manufacturers like TSMC and Samsung, and packaging and testing firms like ASE and Teradyne. These firms specialize in different tasks, often require different skills from their workforces, and locate in different geographies – yet they share a common interest in advancing chip technology to meet a common customer's specifications.

The key questions for this perspective are associated with the links between manufacturing and innovation in the semiconductor industry. How – if at all – do advancements in semiconductor R&D require close interactions with semiconductor production? In other industries, it is clear that engineers developing new products benefit from observing and interacting with the production process. R&D engineers gain new knowledge from co-locating near production. A similar pattern has unfolded in the semiconductor industry with R&D facilities concentrating near fabs. In Albany, NY, for example, SUNY Poly's R&D campus is located near a GlobalFoundries fab and IBM. In TSMC's Arizona investment, for example, the plan is to locate advanced fabs near R&D offices. Moreover, investment in advanced R&D, as well as advanced production, has the potential to stimulate new companies driving innovation in the semiconductor industry, although it is unclear how production investments might support the growth of those companies.

The federal government's vision for the U.S. semiconductor industry draws on each of these three perspectives. It emphasizes national defense priorities, as well as the creation of high-wage jobs. Across multiple domains, it is focused on the United States becoming a technology leader. But there are ways where these perspectives come into tension. Whereas economic security may favor locating more critical suppliers in the United States, the presence of these suppliers may be less central to job growth or advances in innovation capacity.

One viable way to satisfy these three perspectives is to start by prioritizing innovation, cultivating the types of business activities and public-private partnerships that will contribute to U.S. technology leadership. Of course, not all advances in innovation translate into more secure supply chains or widely shared prosperity. However, if the innovation in the semiconductor industry is inclusive of a broad cross-section of actors with a stake in the industry – manufacturers and designers, large firms and small firms, established players and startups – there will be opportunities for U.S. innovation to support advocates of economic security, as well as downstream economic benefits, including good jobs. The challenge is to build an infrastructure for innovation that is open to this array of potential contributors.

CHIPS CHALLENGES

The U.S. government has no clear playbook for achieving its vision to rebuild domestic semiconductor capacity. However, several hypotheses do emerge – they're a set of aspirations for how a thriving ecosystem might come together. In this section, we test those hypotheses and propose adjustments based on available data and historical evidence from U.S. industrial policy, particularly at the state and regional levels. This evidence reveals past successes and failures that can help inform policy implementation in the years to come.

HYPOTHESIS 1. REGIONAL CLUSTERS

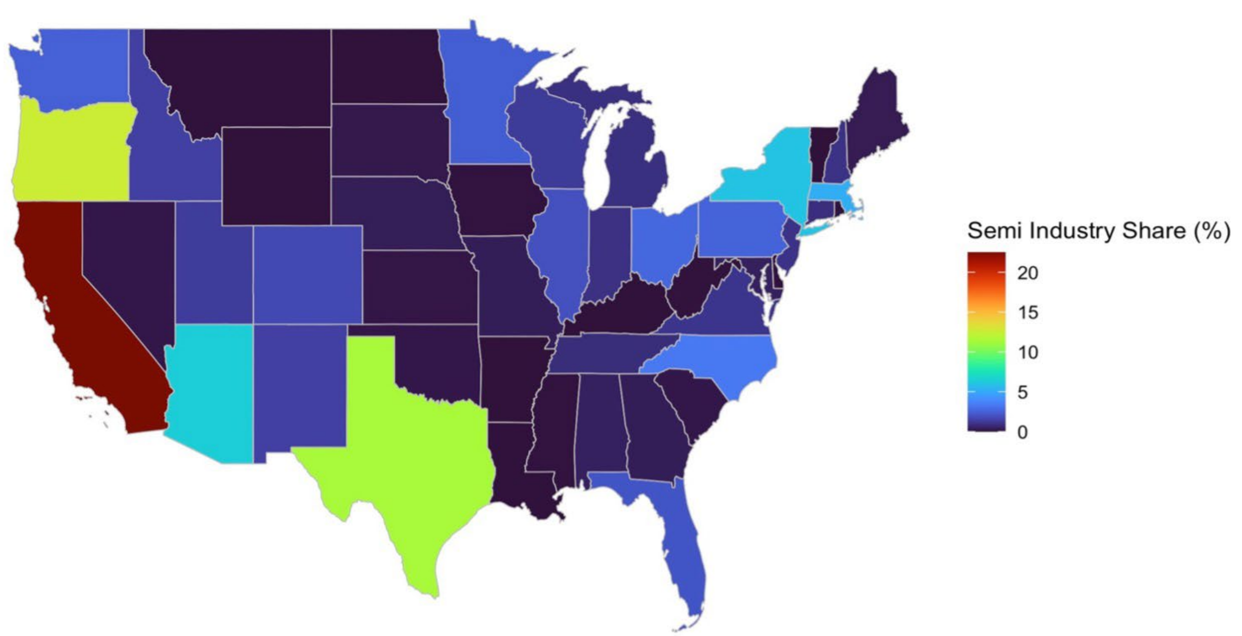
The first hypothesis is that if leading firms build new chip fabs, then suppliers and R&D labs will cluster around them. The U.S. government's vision for clusters even includes a digital rendering of a cluster where fabs are at the center of a campus including specialized infrastructure; assembly, test and packaging facilities; R&D labs; equipment suppliers and materials producers; as well as childcare and training facilities. There is evidence from the Hsinchu Science Park that in some cases, clustering of these related activities does happen. However, this appears to be the exception – not the rule.

To test the hypothesis using existing data in the United States, we gathered manufacturing data on the U.S. states with the largest semiconductor production – states with substantial chip fabs. Six states account for approximately two-thirds of all semiconductor production revenues: Arizona, California, Massachusetts, New York, Oregon, and Texas. Figure 2 represents each state's share of the national semiconductor production revenue. For example, Texas, in green, accounts for approximately 10% of all semiconductor manufacturing related revenues in the United States.

Then, we studied the concentration of related industries in those states. Did materials suppliers, device makers, and equipment manufacturers tend to locate in the same

Figure 2

The Geography of The U.S. Semiconductor Industry[viii]



states as these fabs? Using SEMI's database of firms in the semiconductor supply chain, broken down by category – equipment, materials, fab, and device (defined narrowly as IDMs and fabless firms) – we identified the top industry codes for firms in each industry segment using job posting data. For example, materials suppliers were frequently listed under the "basic chemical manufacturing" industry, and equipment firms were frequently identified as "navigational, measuring, medical and control instruments" manufacturers. Although these industry categories encompass more than the semiconductor industry alone, we should still expect firms in these industries to be more concentrated around fabs than elsewhere in the country.

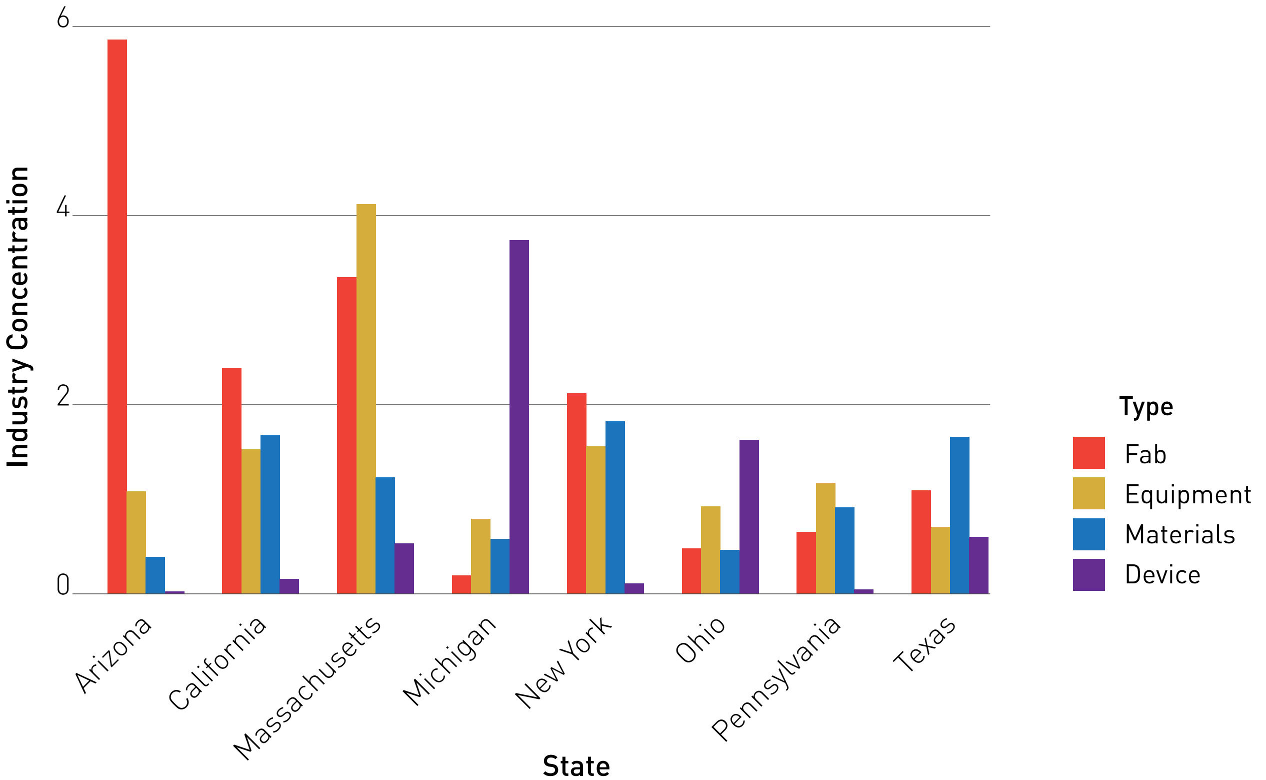
Figure 3 shows mixed results. It graphs industry concentrations in several states, including states with fabs and large manufacturing states without fabs, such as Michigan and Pennsylvania, as points of comparison.[ix] The measure on the y-axis is the state's location quotient in each industry as a share of total manufacturing revenues.[x]

The red bars in Figure 3 highlight a concentration of semiconductor production. In almost each state with high semiconductor production, there is at least one adjacent industry that is also concentrated in that state. In Massachusetts, semiconductor production is collocated with equipment suppliers. In New York, there is a high concentration of equipment manufacturers as well as materials suppliers, along with fabs. Michigan's high concentration of "device" companies is partially due to the high demand for semiconductors in the automotive sector. Some SEMI members in the device category are automakers, which contributes to the high industry concentration in Michigan. In Texas, too, there is a comparatively high concentration of materials suppliers (in Texas, although there are existing fabs, semiconductor production is still only a moderate share of overall manufacturing revenues).

There are several lessons that emerge from these data. The first is that although some clustering appears to happen in some states with chip fabs, it is not guaranteed. The second is the pattern of clustering is not consistent

Figure 3

Clustering in States with Semiconductor Fabs



across locations. In some places, materials suppliers might be more present than equipment manufacturers – in others, the opposite is true. If there has been no clear pattern of industry concentration around chip fabs, then how might the federal government support their vision of regional clusters?

Policies aimed at developing new industry clusters have a long history in the United States. At the state level, cluster strategies date back to the advanced technology policies of the 1980s, which aimed to replace declining, legacy manufacturing industries with high-technology clusters. These efforts largely failed to gain traction. Even the leading scholar of industry clusters, Michael Porter, recognized the sharp limits of cluster policy. He argued that clusters emerge "spontaneously" due to market forces. Governments can't create clusters, but they can reinforce existing clusters with incentives.[xi] Other scholars have gone even further to argue that government should play a more passive role when it comes to clustering, avoiding getting in the way of the market-driven process of innovation and competition.[xii]

But there is a relevant counterexample. In the Albany region, the New York State government dedicated public funds to support advanced R&D at universities throughout the state.[xiii] In the Albany region, they initially funded a Center for Environmental Sciences and Technology Management with the goal of building on SUNY-Albany's expertise in atmospheric sciences. As the new Center developed, the state and IBM recognized promising research at SUNY-Albany on thin films that they saw as relevant to the semiconductor industry. With support from the state, IBM and Tokyo Electron – a large equipment manufacturer – SUNY-Albany invested more than $375 million in a series of new R&D facilities dedicated to nanotechnology and next-generation semiconductor technologies between 2004 and 2009. It was after the establishment of that R&D complex that the region attracted a large commercial wafer fab, which GlobalFoundries began constructing in 2009.

The Albany example suggests *how* government actors might reinforce clustering of R&D facilities near fabs. In the New York case, government served as a scout and a convener, searching for partnerships that the market would not scale on its own. In the New York case, it was a university-industry R&D partnership that required state funding for advanced equipment and infrastructure to scale. In the implementation of the CHIPS Act, the government may look for opportunities to scale similar partnerships that show promise, but do not have the infrastructure to grow.

The data suggest that clusters of materials suppliers, R&D, and equipment manufacturers are not an inevitable result of new fabs – locations with an established base of expertise and operations in the semiconductor supply chain in one location will not automatically move to another. However, pockets of expertise may emerge due to fab investments and market forces. Government policy should not necessarily assume or require clusters from its CHIPS Act investments – the supply chain benefits may be more dispersed, and policies should aim to build on and "reinforce" the clusters that the market helps generate.

HYPOTHESIS 2. WORKFORCE DEVELOPMENT

The second hypothesis is that employers will form workforce development partnerships with educational institutions and community partners to meet a growing demand for semiconductor workers. The U.S. Department of Commerce's implementation plan for the CHIPS Act recognizes that as much as $8 Billion of investment in workforce development efforts, although the Act only covers a small portion of that cost. The Department highlights "best practices" consistent with recent research on sector partnerships that it says will guide investments in workforce development.

Workforce development is justifiably a key priority in CHIPS Act implementation. However, there are steep obstacles to scaling effective workforce development programs in the United States (see "Training a Technician Workforce" insert).[xiv] Moreover, a detailed workforce development plan must identify what types of workers that the industry will need to recruit. Interviews and public statements from semiconductor firms reveal that even similar firms have different hiring and workforce development strategies.

Compare Intel's hiring strategy for its complex of fabs in Ohio to TSMC's hiring strategy for its planned fabs in Arizona. Both companies plan to hire thousands of workers to operate their facilities and perform related R&D. In Ohio, Intel has reported that 70% of its hires will not require a college degree. This is consistent with online job posting data from Intel in Q4 2021, which include a high share of jobs requiring only high school or associate's degrees. At TSMC, by contrast, hiring officials report that nearly all personnel at the Arizona complex will require a college degree or more. This is consistent with online job postings. Among 17 roles posted for TSMC in Arizona, fifteen require a college degree in engineering or above – many with a preference for master's or PhD level education. One job requires an associate's degree, and one does not require any qualification.

The Intel-TSMC comparison highlights at least two tracks for workforce development within the semiconductor industry. One emphasizes the importance of technician-level skills and partnerships with workforce development organizations like community colleges. A second track requires university partnerships. And in the case of recruiting master's and PhD-level graduates, workforce development partnerships might combine R&D with training objectives.

Job postings data across the semiconductor industry help reinforce the idea of two tracks – one for technicians, another for college-educated engineers. Figure 4 plots the educational requirements of job postings from Q4 2021 among SEMI firms in each market segment of the semiconductor industry. The plot includes job postings for engineers, technicians, production workers, and maintenance staff. It shows similar demand for high school graduates and college graduates across multiple segments.

Even with workforce development programs targeting each of the two tracks, there is still a significant risk that companies will find it challenging to fill manufacturing jobs requiring only a college degree. U.S. manufacturing jobs across industries currently suffer from an acute labor shortage, as well as increased turnover. Part of the challenge is a declining wage premium in manufacturing. Whereas production jobs for individuals without a college degree paid more than 40% more than non-production jobs in 1960, they pay only 2% more than alternative jobs in 2021.[xv] As a result, recruiting the necessary workers into factory jobs in equipment manufacturers and chemical producers may prove difficult.

There has been a consistent emphasis that semiconductor jobs are good jobs. It's true that jobs in semiconductor fabs, many of which require advanced training, consistently pay high wages. However, jobs in related sectors such as equipment manufacturing pay wages closer to the median for manufacturing. And while chemicals manufacturing is consistently among the highest-wage manufacturing

Figure 4

Skill Demand in the U.S. Microelectronics Ecosystem

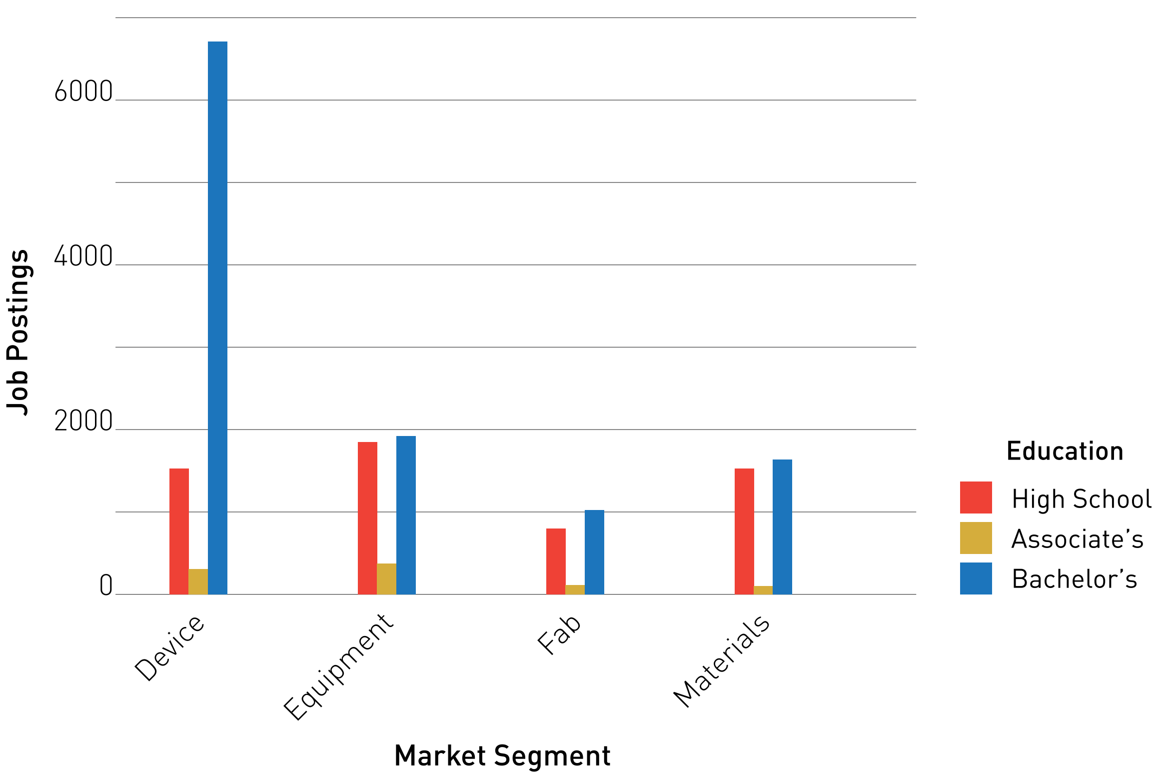
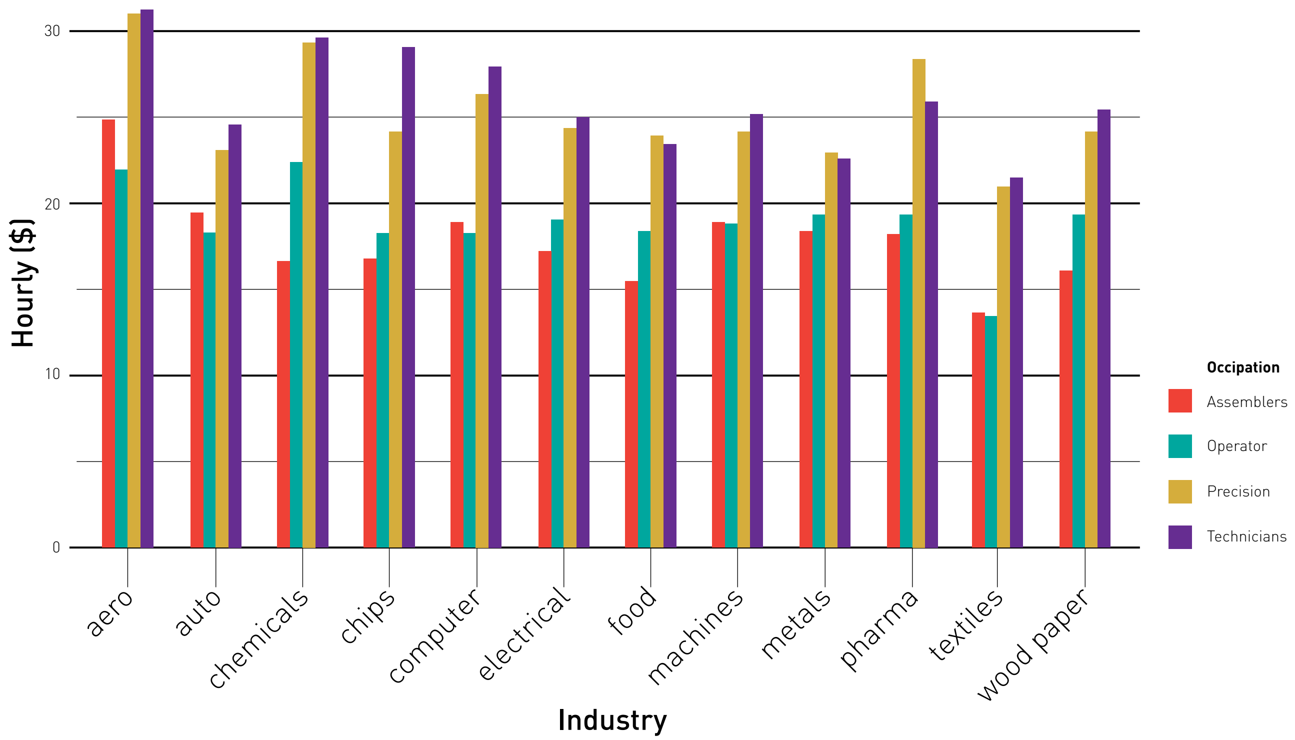


Figure 5
Wages by Industry and Occupation in Manufacturing



sectors for some production jobs, it is less true for other. Figure 5 shows how these broad industries compare to others in manufacturing.

The semiconductor sector, as noted, faces critical workforce needs at every level, including engineeris and technicians and a concerted effort will be required to meet these needs. Industry alliances with universities will be needed on the engineering talent side. Industry collaborations with community colleges and state and local government in sector partnerships can help meet technician needs. Concerning the general manufacturing workforce, these sector partnerships as well as apprenticeships can help, but higher wages in firms where compensation levels are below the manufacturing sector average can be key.

HYPOTHESIS 3. INNOVATION

The third hypothesis is that the presence of a public-private research partnership in the form of the National Semiconductor Technology Center will help foster collaboration between universities and firms to spur innovation in the United States. There is a history of successful research collaboration in computing between industry and universities in the United States, particularly with support from DARPA.[xvi] Although the United States is still a leading source of semiconductor innovation according to patent data, there is evidence that new energy and investment is needed. Figure 6 shows how U.S. patenting has been comparatively flat to other global semiconductor innovators since 2010. And Figure 7 shows how semiconductor patenting in the U.S. has declined as a share of overall U.S. patenting over the past decade. There's a need for a new wave of innovation in semiconductors, but it is unclear how to achieve it.

The vision for R&D and the CHIPS and Science Act related to the semiconductor industry builds on two previous models: SEMATECH and the U.S. network of Manufacturing USA institutes. SEMATECH was a research consortium led by U.S. semiconductor manufacturers including Intel and Texas Instruments in the late 1980s launched to accelerate U.S. competitiveness in response to the rise of Japanese competition. It received $500 million in DARPA funding over five years. The CHIPS and Science Act establishes a National Semiconductor Technology

Training a Technician Workforce

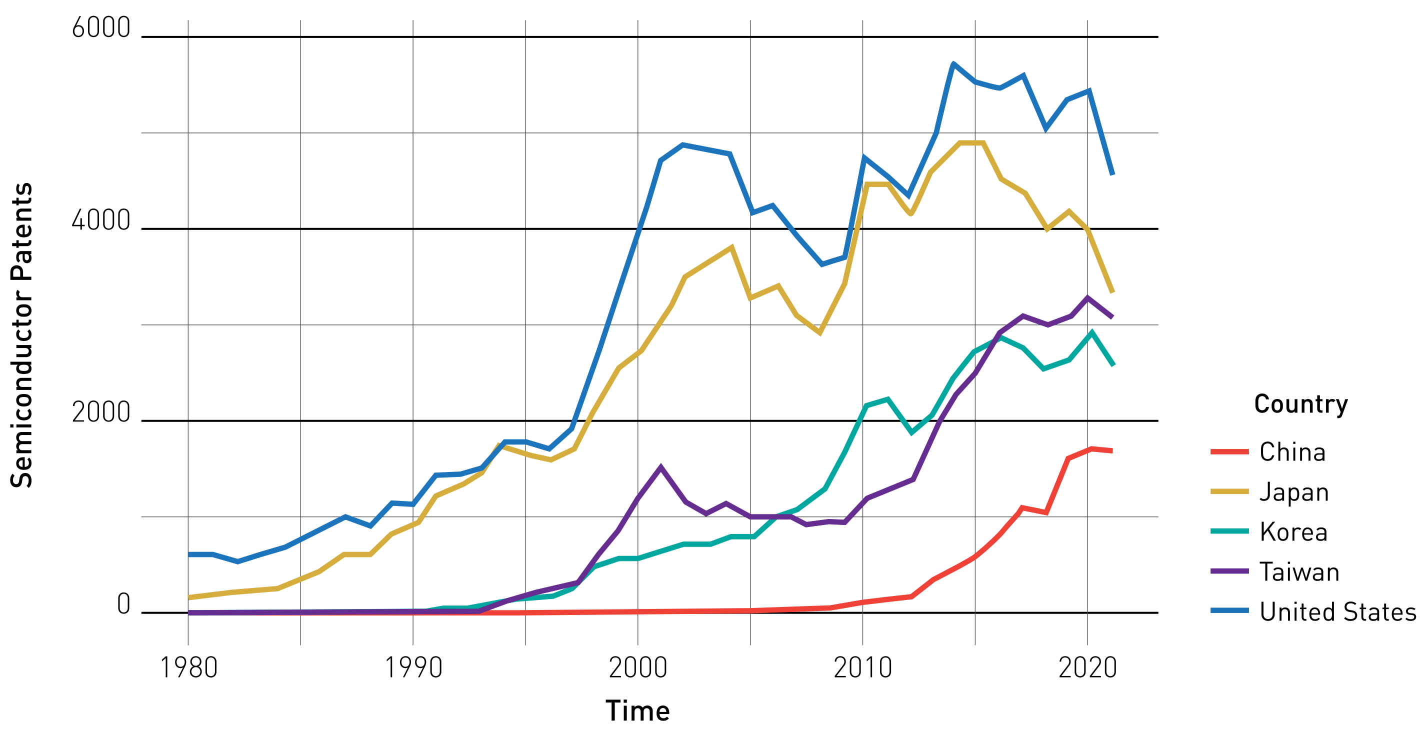
The workforce education system in the United States faces deep challenges when it comes to training technicians. Research has identified opportunities for how to strengthen the broader workforce development system in the United States. Three key points emerge from this work.

1. Bridge the gap between work and learning. Lifelong learning to update or learn new skills is largely missing from the U.S. system, and the labor market information system to help employers and employees find the skills they need is broken. Nonetheless, there have been success stories where employers have worked with community colleges on new education programs, and there is a growing effort in some areas to implement a work-learn-earn apprenticeships.

2. Renew public investment in advanced skills. Government and industry have been disinvesting in workforce training for decades and those numbers are only recently starting to improve. The government's Labor Department programs reach largely un- or underemployed workers, not advanced skills or upskilling for incumbent workers, and its Education Department programs are aimed at college support – not workforce education. Workforce development investments from the CHIPS and Science Act can help refocus public programs for semiconductors on providing advanced skills that allow American workers to enter better careers. One model with a strong track record is "sector partnerships," which requires employers to identify common skills they need, and enlists community organizations to coach and support workers as they transition jobs.

3. U.S. community colleges are underfunded with completion rates that are far too low. Regarding semiconductor work, training in software dominates college computer science programs compared to electrical engineering fields relevant to semiconductors. Support for the semiconductor technician workforce should aim to alter this imbalance and expand the relevant talent pool.

Figure 6
Global Innovation in the Semiconductor Industry



Center (NSTC), as well as a National Advanced Packaging Manufacturing Program (NAPMP), which seem modeled on the SEMATECH consortium meant to support research coordination among industry with federal support.

The Manufacturing USA Institutes (also known as the Manufacturing Innovation Institutes) emerged out of the Obama Administration's Advanced Manufacturing Partnership in 2009. The Institutes are charged with numerous activities, most prominently to help broker public-private research partnerships around core technology challenges. The CHIPS and Science Act reserves funding for as many as three more Manufacturing USA Institutes related to semiconductor technologies.

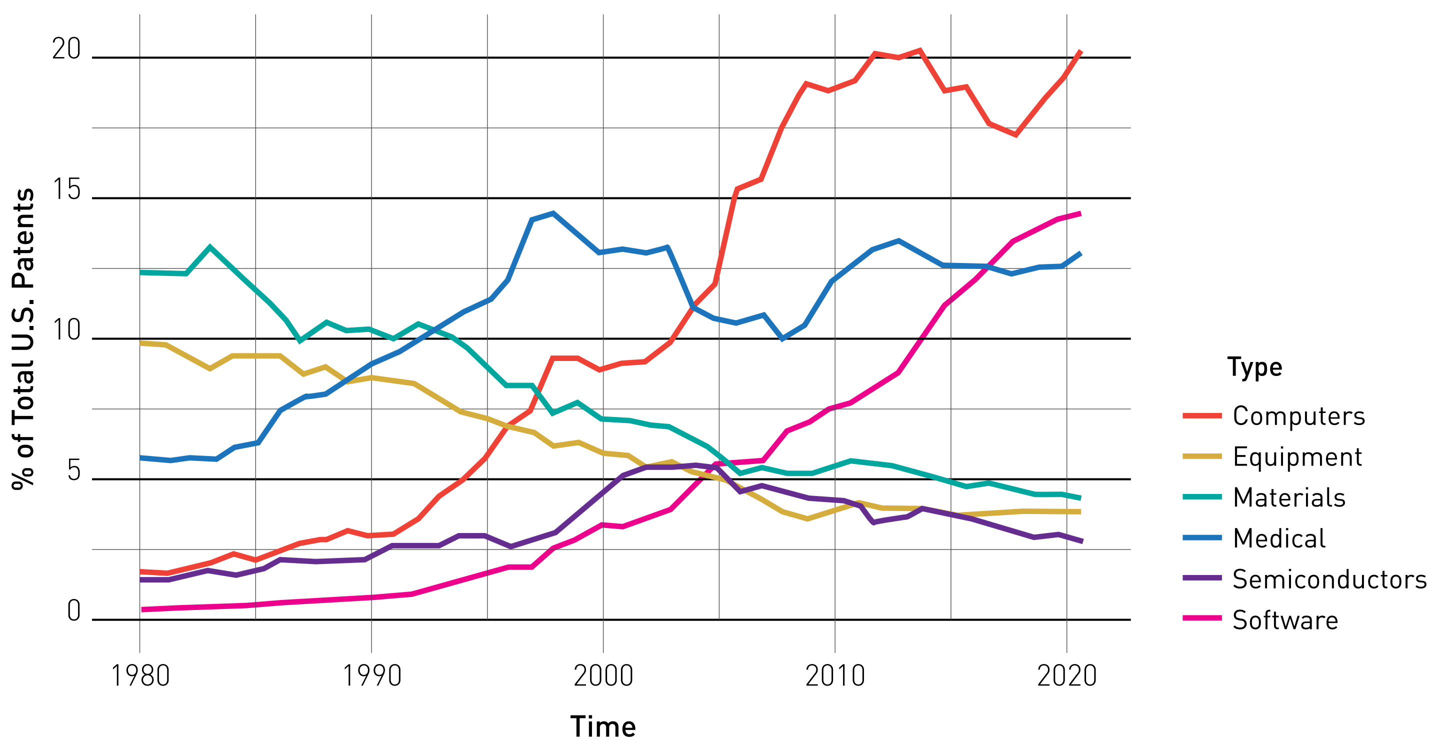
In establishing the NSTC and new Manufacturing USA Institutes, it is important to reconsider the limitations of SEMATECH – which shut down in 2015 – and the current Manufacturing USA network.

First, the SEMATECH and Manufacturing USA models focus on generating domestic innovation, but the current R&D process in the semiconductor industry requires global cooperation between companies based the world over. Initially, SEMATECH helped establish a technology roadmap and technology standards among U.S. semiconductor manufacturers. But with a global ecosystem of manufacturers and suppliers, what role does the NSTC expect to play in facilitating or accelerating this research and development process, or ensuring that the knowledge that emerges is captured in the United States? Although there is an opportunity for the NSTC to scale university R&D, there have been criticisms in public documents that technology in university labs lag far behind the cutting edge of the industry.

Second, the Manufacturing USA model has faced challenges including small and medium sized companies. Because the manufacturing institutes initially were only funded short-term by the government, they had to depend on larger firms for support. Small and medium manufacturers are less likely to afford matching costs for participating in R&D projects or have an established team to engage in long-run research activities. Moreover, large companies have been reluctant to engage in joint research with other firms that they consider behind their level of technological advancement.

Figure 7

U.S. Innovation by Technology Area



SEMATECH had a different but similarly relevant model. SEMATECH began with a model of “horizontal collaboration” between firms with similar roles in the ecosystem, such as chip manufacturers. Over time, in response to concerns that smaller chip manufacturers might “free ride” on more advanced companies, it evolved to support “vertical collaboration” between leading fabs and their equipment and materials suppliers.[xvii] Not finding research collaboration valuable, SEMATECH struggled to retain industry participation, particularly among equipment manufacturers. Manufacturing USA Institutes have also struggled to engage smaller firms – but for different reasons.

Third, both models generally miss an opportunity to facilitate the creation of new startups that spin out of university labs and established semiconductor firms. There has been a long-run decline in the share of manufacturing startups in the United States. In the mid-1980s, approximately 37% of manufacturing firms were startups – they had been established in the previous 5 years. But by 2015, the number was down near 20%.

The startup problem in manufacturing is especially significant given the legacy of innovation in the U.S. semiconductor industry, which came primarily from spin-offs from one semiconductor firm to another through the 1960s. With available research capital – and a commitment from the federal government to support demand for U.S. chips – there is new potential for entrepreneurs with industry knowledge to spin out their own enterprises. This is particularly important because technologies outside the CMOS paradigm may be needed to improve chip performance in the long term. However, neither the CHIPS and Science Act, nor regional efforts focused on semiconductor manufacturing, invest in supporting this channel for innovation.

CHIPS and Science Act funding, then, can help fund the significant R&D that will be needed for ongoing semiconductor sector advances. However, a model that embraces both fabs and smaller equipment, materials and device firms will be needed, and both the Manufacturing USA institutes and SEMATECH offer lessons on issues to avoid in this regard. In addition, a focus on innovative startups will be needed given the complexities of the next generation of technology challenges.

Lessons for CHIPS Act Implementation

There has been widespread discussion of the CHIPS and Science Act as the beginning of a new chapter in American industrial and innovation policy. Indeed, the scale of the federal government’s commitment to supporting industry is unprecedented in the past 50 years. However, there are precedents for understanding where government interventions can help drive innovation and good jobs – and where government intervention in the market may fall flat. In economics, there is an ongoing debate over the merits of industrial policy and the conditions under which it can succeed. There is clear evidence from countries like Japan, South Korea, and Taiwan that state-led industrialization can contribute to rapid economic growth. In the United States, there are also examples of state-led innovation policies at agencies like DARPA contributing to the commercialization of new technologies.

These precedents suggest that the U.S. government’s ambitious vision for the CHIPS and Science Act is achievable, but not guaranteed. It will depend on implementation – making specific choices about how to incentivize clustering, fund workforce development, and organize centers of innovation. Three lessons from past policies and current data can inform these efforts.

1. GOVERNMENTS ARE GOOD CONVENERS AND SCOUTS

As the CHIPS Office and its partners look to support clusters, they can play a role as convener of actors that might not have otherwise collaborated – such as SME suppliers and large OEMs, or university labs and firm R&D teams – as well as scouts for promising technologies and ideas that have potential to scale, but are missing the expertise or capital to do so. In both cases, the market does not always make matches or support scale-up on its own. Government can contribute with the benefit of funds the CHIPS and Science Act has made available.

2. THREE SEMICONDUCTOR WORKFORCES REQUIRE THREE WORKFORCE DEVELOPMENT APPROACHES

For the engineering workforce, R&D partnerships with university labs that support undergraduate and graduate students can double as workforce development. For the technician workforce, a sector partnership model requiring collaboration and curriculum setting from employers (in partnership with community colleges and others) has proven effective in other settings and is consistent with the "best practices" stated in the CHIPS Act.[xviii] This mechanism can be important for semiconductor technician training. Although the sector partnership model has shown promising results in some settings, it is expensive to scale. For the largest segment of the semiconductor workforce – the general manufacturing worker requiring only a high school degree – building the workforce pipeline will prove more challenging as turnover increases and the labor shortage persists. The most reliable workforce development tool will be higher productivity factories that pay higher wages.

3. PAVE THE WAY FOR STARTUPS

The precipitous decline of U.S. manufacturing startups limits the potential of innovation in the semiconductor industry. Without established channels for startups to spin out of university labs or established firms and scale, all the paths to commercialize new technology must go through established firms. Starting and scaling new enterprises has long been a comparative advantage for the United States. And startups have a strong record in contributing to new job growth.

Governments have a mixed track record as venture capitalists with prominent failures attracting more attention than long-term successes like DARPA.[xix] Despite high barriers to entry in the semiconductor industry, there are opportunities for regional hubs to attract risk capital and facilitate new startup formation. The CHIPS and Science Act cannot replicate Silicon Valley, but it can help facilitate some of the same knowledge spillovers and entrepreneurial spirit that helped energize the U.S. semiconductor industry in its earliest decades.

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x If the location quotient is 1, that means the industry is as concentrated in the state as it is in the United States as a whole. If it is 1.5, it means that the industry is 50% more concentrated in the state than it is in the United States. If it is .5, for example, it is 50% less concentrated in the state compared to the concentration of the United States. As an illustrative example, equipment manufacturing in New York is 9.21% of the state's manufacturing revenue. It's 5.85% of manufacturing revenue in the United States. New York's location quotient in equipment is 1.57, indicating that its share of manufacturing revenue in New York State is 57% higher than the share of revenue from equipment in the United States.

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