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Semiconductors and U.S. Industrial Policy

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About the Author

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About the Report

This report is published as part of the U.S. National Industrial Policy Strategy project at the Center for a New American Security (CNAS). The project is developing an intellectual framework for industrial policy in the American context, in an era of strategic competition with technology at its center. The goal of the project is to pave the way for enhanced and sustained U.S. economic competitiveness and technological leadership. This report builds on analysis and insights from prior CNAS publications, including:

- "Reboot: Framework for a New American Industrial Policy," by Megan Lamberth, Martijn Rasser, Hannah Kelley, and Ryan Johnson (May 2022).
- "Regenerate: Biotechnology and U.S. Industrial Policy," by Ryan Fedasiuk (July 2022)
- "Reimagine: Clean Technology and U.S. Industrial Policy," by Jonas Nahm (September 2022)
- "Rebuild: Toolkit for a New American Industrial Policy," by Emily Kilcrease and Emily Jin (September 2022).

Additional reports from this series are available on the project page.

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The Energy, Economics, and Security Program analyzes the changing global energy and economic landscape and its national security implications. From the shifting geopolitics of energy to tools of economic statecraft, such as trade and investment policy and sanctions, the program develops strategies to help policymakers understand, anticipate, and respond. The program draws from the diverse expertise and backgrounds of its team and leverages other CNAS experts' strengths in regional knowledge, technology, and foreign policy to inform conversations at the nexus of markets, industry, and U.S. national security and economic policy.

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Executive Summary

As the United States considers industrial policy for the first time in decades, it should learn lessons from prior government efforts to shape the semiconductor industry, in the United States and abroad. The U.S. government has played a major role in the semiconductor industry since the invention of the first integrated circuit, via funding scientific research and via military procurement, which has driven the commercialization of new technology. However, though government—and specifically, the Defense Department—has had deep connections with the chip industry, it has played only a supportive role in building America's semiconductor industry, with the key innovations and firms emerging from private sector expertise.

Other countries have experimented with industrial policy toward semiconductors, too. Success stories in industrial policy generally have involved investing in skilled workforces and ensuring competitiveness by pushing domestic firms to sell to international markets. Simply pouring capital into a country's chip industry rarely has been a winning strategy.

Today, the U.S. government should focus policy toward the semiconductor industry around four main objectives: promoting technological advances, guaranteeing security of semiconductor supply, retaining control of choke points, and slowing China's technological advances. Key recommendations on these themes include:

- Promoting technological advances.
  - Invest in workforce development.
  - Reform visa issuance to ensure world's leading chip experts can work in the United States.
  - Focus new funding on technology development and prototyping.
- Guaranteeing resilience and integrity of supply.
  - Invest in techniques to identify semiconductor security flaws.
  - Build additional semiconductor expertise in the U.S. government.
  - Mitigate supply chain dependencies on adversaries.
  - Diversify the fabrication base.
- Retaining control of choke point technologies.
  - Prioritize research and development support around choke points.
  - Deepen export controls around manufacturing equipment, including component parts, with allies.
- Working with allies to retain U.S. technological advantage versus China.
  - Offer China a deal to limit chip subsidy schemes.
  - Limit foreign investment in China's chip industry via outbound investment controls.
  - Intensify export controls on choke point technologies.
  - Address Chinese chip subsidies via export controls and sanctions.

The history of industrial policy suggests that government can play a productive role in supporting workforce development and in funding research and development and prototyping. Moreover, the government has a clear role to play in addressing the security challenges posed by the excessive concentration of the industry's fabrication and assembly capability in and around China, which presents an acute risk of disruption in case of geopolitical crisis. To start, however, the U.S. government must deepen its expertise in the industry to ensure policymakers understand the complex supply chains that undergird the semiconductor industry and produce the computing power that U.S. prosperity and security depends on.

Introduction

Driven by widespread shortages and the weaponization of semiconductor supply chains for geopolitical purposes, U.S. political leaders are devoting substantial attention to semiconductors for the first time in decades. As China pours subsidies into its chip industry—and as fabrication capacity for advanced processor chips continues to concentrate in East Asia—concerns about the security of America's semiconductor supply are growing. So, too, is discussion about whether the U.S. government needs a strategy toward the semiconductor sector, and if so, what this strategy should look like.

Demand for semiconductors, also known as chips or integrated circuits, has grown rapidly as the economy's need for computing power grows. The integrated circuit was invented in the United States, which still plays the biggest role by far in the international semiconductor industry. However, the chip industry today relies on supply chains that stretch across the United States, Europe, and Asia, which have provided the efficiency that have made possible dramatic increases in computing power at decreased cost. With several thousand manufacturing steps needed to fabricate an advanced chip, there is hardly a semiconductor in the world that does not require materials, machinery, and designs from a dozen countries. In the past, it was possible to make most chips using materials and machines from only a handful of countries, primarily the United States and Japan. As the industry has grown more complex, reliance on other countries, especially Taiwan and South Korea, has grown.

Today, semiconductors are crucial not only to most types of manufactured goods. They also are a crucial ingredient in geopolitical influence and military power. The types of military equipment that will define the future of war, from advanced electronic warfare systems to autonomous drones, will rely heavily on semiconductors to sense, remember, process, and communicate information. Even decades-old systems, such as the Javelin missiles that have proven so effective against Russian tanks in the Russia-Ukraine War, require more than 200 semiconductors to function.[1] Next-generation systems will be even more reliant on computing power.

Semiconductors are not only important in producing military power but also are a tool of geopolitical influence. All the world's great powers are weaponizing parts of the semiconductor supply chain. In 2019, Japan placed restrictions on the export of certain chemicals to South Korea, with which it was in a political dispute.[2] In 2022, Russia has halted the export of certain noble gases needed in chipmaking, hoping to exacerbate global semiconductor shortages and intensify inflation in Western economies.[3] The United States has cut off prominent Chinese firms such as Huawei from accessing certain types of chips produced with U.S. tools or software. In addition, after Russia's invasion of Ukraine in February 2022, the United States and several allies imposed export controls to de facto prevent Russia from acquiring any advanced chips without U.S. or allied government approval. Most prominently, China is spending billions of dollars on subsidies to domesticate advanced semiconductor technologies, which China sees as a means to advance its technological capabilities and reduce its vulnerability on foreign technology, and which, if successful, also would reduce the cost to China of attacking Taiwan.

With one of the most internationalized supply chains, the semiconductor industry is as exposed as any sector of the economy to increasing geopolitical tensions. The fact that almost all the world's most advanced processor chips are produced in Taiwan—an island that China's leaders insist is theirs—only adds to the vulnerability. So, too, does that fact that Chinese analysts employed by the government are talking openly now about invading Taiwan to seize its chipmaking facilities.[4] The fact that such a gambit would be unlikely to work, given the immense sensitivity of chipmaking facilities and their reliance on U.S. technology, does not detract from the fact that influential Chinese thinkers see it as a plausible strategy.

It is no surprise that leaders in the United States, alongside many allied countries, are beginning to think seriously about semiconductors. Recently, Congress enacted legislation that could substantially reduce the cost differential between building chipmaking facilities in the United States versus in East Asia, though the amount of funds under discussion will be far from enough to make up for the cost gap across the industry.[5]

However, for industrial policy in the semiconductor space to succeed, it must be focused on achieving concrete goals. Complete onshoring of the chip industry is a fantasy, though there is much that can be done to secure supply chains from reliance on adversaries or mitigate risks in case of war. The U.S. government is unlikely to predict technological trends, understand supply chains, or invest in winning firms as effectively as private market actors. What it can do is support the development of a skilled workforce, facilitate researchers and startups' access to advanced chipmaking tools and fabrication, adjust tax policy to reduce the high cost of manufacturing in the United States relative to Asia, and limit China's access to advanced technologies. This report explores current trends in the chip industry, and the history of industrial policy in the United States and abroad, in providing recommendations for policymakers about how to approach semiconductors.

NODES OF A SUPPLY CHAIN AND KEY INPUTS REQUIRED

1

Chip Design Expertise
Firms with knowledge in circuit design create the architecture for each chip.

IP, specialized design skills

2

Electronic Design Automation (EDA) Software
Software tools used to design chips and verify they will perform as expected.

IP, specialized knowledge

3

Manufacturing Equipment
Semiconductor manufacturing requires many pieces of equipment to undertake the hundreds of ultra-precise process steps needed to fabricate an advanced chip.

Precise components, unique materials, specialized expertise

4

Fabrication
Chipmakers manufacture chips in facilities ("fabs"), using manufacturing equipment to etch chip designs onto silicon wafers.

Manufacturing equipment, specialized software, silicon wafers, chemicals, specialized expertise

5

Chip Packaging and Assembly
The process of encapsulating chips to protect them from damage and prepare for connection with electronic devices.

Equipment, chemicals

6

Assembly into End Products
The process of putting the packaged semiconductors into the end products ranging from consumer goods to industrial equipment.

Labor, manufacturing equipment wafers, chemicals, specialized expertise

The History of U.S. Industrial Policy toward Semiconductors

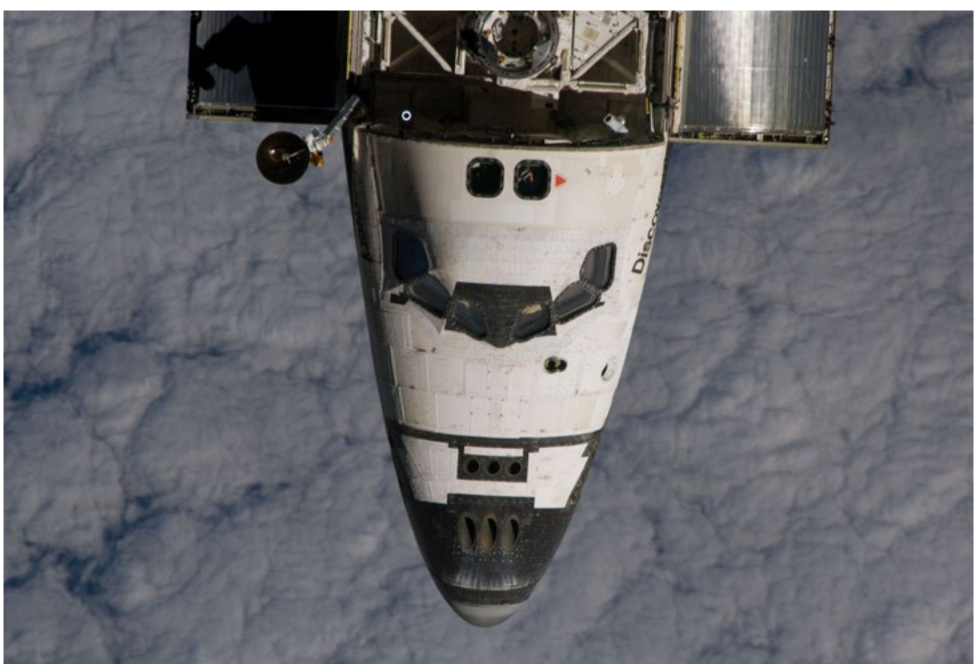
Efforts to craft policy toward the chip industry can learn from the long history of U.S. government engagement with the sector. Today, unlike in the past, the government demand for defense and other purposes accounts for only a small percentage of all chips purchased, with the Defense Department's purchases constituting 1 percent of semiconductor industry revenue.[6] The vast majority of chips produced serve civilian markets. However, the U.S. government is an important customer for certain types of chips—for example, radiation-hardened chips used in space systems or certain types of radio-frequency chips or sensors. Government purchases can play a major role in shaping these niches but rarely impact the biggest commercial players. The U.S. government therefore finds itself responding to trends set by industry as often as it is shaping them.

Government has sought a role in the chip industry since its foundation, but government action has sometimes helped, sometimes hurt. In recent years, some pundits have argued that because government has funded basic research into many advanced technologies, the government is a reliable venture capitalist.[7] There is a grain of truth in this interpretation, but it is mostly wrong. The U.S. government has played a role in funding a healthy research and development (R&D) ecosystem in microelectronics, supporting university researchers, and providing demand for cutting-edge products. However, what has differentiated the United States from other countries—many of which also have government programs to fund advanced technologies—is that U.S. firms have had strong incentives to commercialize products and produce them at scale, private-sector venture funding that enabled large-scale risk taking, and vast consumer markets into which mass-produced goods can be sold.

To succeed, U.S. industrial policy efforts today must learn the right lessons from Silicon Valley's history. Institutions such as the National Science Foundation play an important role in funding basic research, while the Defense Department has bought small-batch prototypes of new technologies for military systems, which eventually can be commercialized at scale. However, counting on the government to be an effective venture capitalist, private equity investor, or corporate manager is a bad bet that is just as likely to create problems as it is to solve them.

Defense Funding and the Origins of the Semiconductor Industry

The semiconductor industry emerged out of the Cold War defense industrial base. Fairchild Semiconductor and Texas Instruments (TI), the first two companies to invent and commercialize integrated circuits, were attracted to the microelectronics business because of the U.S. military's vast demand for sensors and communications devices amid the defense buildup of the early Cold War. Texas Instruments received an Air Force research contract to study integrated circuits just months after TI employee Jack Kilby devised one of the first integrated circuits in 1958. Fairchild won the first large-scale procurement contract for integrated circuits shortly thereafter, when it was chosen to help produce the electronics in the guidance computer that directed the Apollo



Specialty chips are crucial inputs for niche end-uses. The space shuttle Discovery's mission in 2009 required radiation-hardened chips. (NASA/Getty Images) spacecraft to the moon. Texas Instruments' first major customer for its chips was the U.S. military, which used integrated circuits in the guidance computer on the Minuteman II intercontinental ballistic missile.[8]

The surge of defense and space spending on microelectronics in the 1950s and early 1960s catalyzed the development of integrated circuit technology and placed U.S. companies in a leading position. Defense and space customers had unique product demands that pushed technological development forward. To increase the range of Minuteman missiles or of Apollo spacecraft, for example, volume, weight, and power consumption of guidance systems had to be minimized far beyond the demands of any civilian system. Unlike civilian customers, moreover, NASA and the Pentagon were willing to pay high prices for small-volume production runs. At the time, no comparable civilian user existed, so without the funding provided by the arms race, the microelectronics industry likely would have taken a different and possibly slower development path.

It would be wrong, though, to see the emergence of integrated circuits as a case study in the ability of government to pick winning technologies or firms. Many parts of the U.S. government were more optimistic about an alternative paradigm of microelectronics research called "molecular electronics"—which quickly sputtered out.[9] In 1959, just as the first integrated circuits were being fabricated by Fairchild Semiconductors and Texas Instruments, the U.S. military commissioned a study of the future of miniaturized circuit technology and the firms and labs that were conducting research into the topic. The researchers visited 15 firms and research labs, including TI and Fairchild, major defense contractors like Hughes Aircraft and Lockheed Martin, and electronics giants like the Radio Corporation of America and Philco, which were major producers of then-cutting-edge technologies like radios and vacuum tubes. The researchers reported no evidence that Fairchild and TI were on the brink of pioneering a new industry.[10]

A government's role is to nurture industry by providing a healthy ecosystem, not to try to replicate industry's capabilities.

Though the government poured research funds into microelectronics, many of the crucial innovations in the early chip industry didn't happen via government programs. The Defense Department funded around a quarter of semiconductor industry R&D in 1958, the year the integrated circuit was invented, and through the late 1960s government still spent more than industry on semiconductor R&D.[11] However, neither of the co-inventors of the integrated circuit at Fairchild or TI were conducting research on government contracts. Defense research dollars spurred interest in semiconductors, while defense and space procurement ensured that new microelectronics ideas had a good chance of finding a military market. But the government played no direct role in conceiving of the revolutionary idea of putting multiple electronic components on a single piece of silicon. And it was the consumer market that provided the chip industry the volume of sales needed to scale production.

When it came to decisions about procuring integrated circuits, the initial NASA and defense contracts were decided by open competition between established firms and startups like Fairchild. The big, legacy firms routinely performed worse. For example, in the Apollo program, the MIT computer expert charged with devising the spacecraft's guidance system ordered chips from multiple suppliers while testing components for the computer. He ended up choosing Fairchild's chips because competitors such as General Instruments, Signetics, Motorola, and Westinghouse—which were then big names in the electronics industry and major defense contractors—delivered chips behind schedule or with performance defects. All of Fairchild's orders arrived on time and substantially below competitors' prices. The decision to guide the Apollo spacecraft to the moon using Fairchild's integrated circuits, which were an untested product produced by an unknown firm, was a risky bet. It was illustrative not of a heavy-handed industrial policy but a decision to rely on clear performance targets and market competition to find the best suppliers.[12] Defense and space customers were a crucial source of demand for integrated circuits, buying nearly every integrated circuit produced in 1962, half by 1966, and still 40 percent by 1968.[13] But there was no "industrial policy" behind it beyond a vast budget for building more accurate rockets.

The use of integrated circuits for defense and space applications in the early 1960s transformed the guidance computers in spacecraft and missiles. This was crucial for America's Cold War arms race, but it was a tiny market. The earliest chips were far too expensive to be used in civilian computers. Integrated circuits began winning market share in the electronics industry only after companies like Fairchild and TI took products conceived of for defense uses, slashed prices, and repurposed them for civilian purposes.

Startups like Fairchild were fixated on bringing their chips to consumer markets because they had no other way to grow. The big electronics firms and defense contractors already had stable businesses and they struggled to understand the ways integrated circuits could disrupt established markets. Fairchild founder Robert Noyce, by contrast, had previously worked on a defense contract at a company called Philco, which at the time was a major East Coast radio producer. During his work at Philco, Noyce concluded that military research contracts stifled the type of innovation needed to reach consumer markets. Though the NASA contract for the Apollo program helped Fairchild get off the ground, Noyce immediately tacked toward consumer markets, slashing prices to reach a broader civilian market. Integrated circuits that sold for $50 in 1962 had fallen to around a dollar a decade later. By 1968, a decade after the first integrated circuit was invented, 75 percent of chips sold went to consumer applications.[14] Today, almost all do.

The chip industry's origins provide important lessons for industrial policy today. First, a government's role is to nurture industry by providing a healthy ecosystem, not to try to replicate industry's capabilities. Second, government procurement must provide space for innovative startups, not only established firms with more lobbying power. Third, government can play a crucial role not only in funding R&D but also in providing a market for prototypes and low-volume production.

R&D Funding during the 1970s

As the chip industry expanded during the 1970s and firms like Intel and IBM grew rapidly by selling mass-produced chips to civilian markets, government support for the semiconductor industry declined. Key innovations in the 1970s emerged from companies' efforts to target civilian markets. IBM devised the first dynamic random access memory (DRAM) chip to provide more reliable memories for corporate computers. This type of chip, now dramatically more advanced, remains crucial to computers and data centers today. Meanwhile, Intel pioneered the first commercial microprocessor—a generalizable logic chip of the type that today powers computers and smartphones—while working on a contract with a Japanese firm to build chips for a pocket calculator.

Government support remained relevant in pushing forward technological development beyond the scope of what industry was able or willing to fund. In 1976, the Defense Advanced Research Projects Agency (DARPA) funded a report by three leading academics to identify limits to further miniaturization of semiconductor components that industry was not prepared to overcome. The report identified six challenges for future miniaturization of semiconductors, concluding that two of the six could be easily accomplished by industry, and recommending the annual allocation of $500,000—a tiny sum relative to Pentagon budgets—to support research into the other four questions.[15]

Each of the four topics identified in the report posed a long-run challenge to the chip industry's technological development, relevant not to any specific firm or product, but to the entire industry's future chipmaking capabilities. One of the dilemmas identified was how to design chips with not thousands, but millions of components, which, unlike existing practice, couldn't be designed by hand. Having identified this as a challenge, DARPA began funding new ideas for chip design methodologies at universities and research labs, as well as seminar series with leading academics and computer scientists.

A comparatively small amount of research funding into chip design methods eventually produced a new industry of chip design software pioneered by academics (who themselves were often funded by DARPA) in the United States. The industry of providing chip design software today is dominated by a trio of U.S. firms. DARPA funded this research because it perceived military uses for advanced chips, but its support for new chip design methods benefited U.S. chipmakers as well. No less importantly, it helped forge a new industry for chip design software that the United States currently monopolizes—and which provides one of the choke points that makes U.S. export controls in the semiconductor sector so powerful.

American firms face fierce competition from firms in the Asia-Pacific and Europe. Pictured here are workers in a 12-inch wafer chip fabricating plant in New York. (Mario Tama/Getty Images)

Industrial Policy and the U.S.-Japan Semiconductor Trade War

Beginning in the late 1970s, the U.S. chip industry began facing a new source of competition: DRAM producers in Japan. The U.S. government responded in several different ways, including by redoubling efforts to support R&D, but also by heavy-handed and unsuccessful use of tariffs to shift trade patterns. The industrial policy overreach of the 1980s holds lessons for U.S. policymakers today.

During the 1980s, when U.S. firms faced intensified foreign competition, DRAM was the most widely produced type of chip. DRAM chips advanced on a regular cadence, and the only differentiating features between companies' DRAM chips were price and the rate at which a given firm's DRAMs malfunctioned. At the end of the 1970s, Japanese competitors like Toshiba and NEC had learned to produce DRAMs as advanced as Silicon Valley's, but with lower prices and far lower defect rates. One study found that Japanese chipmakers averaged a tenth as many defects as one big American firm.[16]

Japanese firms had two major advantages in producing DRAM chips. First, unlike Silicon Valley's leaders, Japanese firms focused intently on manufacturing quality. To catch up, U.S. semiconductor executives began visiting Japanese chipmakers and trying to emulate their manufacturing methods. A second advantage for Japanese chipmakers was that they benefited from a lower cost of capital—a major issue in an industry in which each new chipmaking fab required large capital investment.[17] Part of the differential between U.S. and Japanese capital costs was due to U.S. interest rates, which were high in the late 1970s and early 1980s as the U.S. Federal Reserve kept monetary policy tight to reduce inflation. Yet part of the differential was caused by the structure of the Japanese financial system, where banks were flush with deposits and thus offered lower interest rates on loans. As long as Japanese firms faced a lower cost of capital, they more easily could fund large-scale investment programs.

Far less important than the prior factors—but far more widely discussed—were Japanese government programs to support corporate R&D efforts, such as the VLSI Program, which pooled R&D funds from several leading Japanese chipmakers and added government funds too. The aggregate spending on the very large scaled integration (VLSI) program was minor, about the same as the R&D budget of a major U.S. chipmaker like Texas Instruments.[18] Research on the program has not shown conclusively that it had a major impact. However, the program loomed large in U.S. thinking and led many Americans to conclude Japan's chip firms benefited from unfair government support.

U.S. industry eventually responded to Japanese competition by focusing on new more complicated products, like the Intel microprocessors that came to define the PC industry. U.S. industrial policy, however, was reactive, defensive, and largely ineffective. One initiative was to threaten tariffs on Japanese imports, leading to a deal in which Japan promised to increase the price at which its companies sold chips worldwide. This ended up doing little to help the U.S. DRAM industry, as most U.S. chipmakers still were forced out of the market. Meanwhile, higher prices for Japanese chips gave space for newer Korean producers to undercut them on price.

Today two of the world's three major DRAM producers are Korean. The only remaining U.S. DRAM producer, Micron, emerged simultaneously with the Japanese challenge and won market share against Japanese and U.S. challengers alike via innovative, cost-cutting manufacturing methods. The use of tariffs as an industrial policy tool was a failure.[19] Had the tariffs also applied to South Korean firms, they would have provided more help to U.S. DRAM producers—but they also would have driven up memory chip prices at a time when the PC industry was just taking off, potentially delaying its emergence.

Sematech and the Limits to Industrial Policy

The second major government initiative to support the chip industry was to create Sematech, a collaborative research institute, partly funded by industry and partly by government, to expedite technological development by U.S. firms. Sematech was intended to emulate Japan's VLSI Program. Bob Noyce, who had founded Fairchild and Intel, was recruited to lead the organization. Around half of Sematech's budget during the late 1980s was directed toward an effort to boost the production of advanced lithography machinery, a crucial chipmaking tool that had been pioneered in the United States but by the late 1980s was being produced mostly by several firms in Japan and the Netherlands. Noyce declared that, "Sematech may likely be judged, in large part, as to how successful it is in saving America's optical stepper makers," referring to the U.S. lithography firms.[20] By this metric, Sematech failed, as the leading U.S. lithography firms went bankrupt or were bought out. Today the United States relies on Dutch and Japanese suppliers of lithography tools.

Sematech's other efforts to bolster the production of chipmaking tools was mixed. For example, leaders of

U.S. chipmakers kept up with Japanese competition in the 1980s by innovating on their technology and their manufacturing processes to keep delivering quality products and low prices.

the effort to build a Sematech-funded reticle inspection tool at KLA, a California company, disagree about whether Sematech support was important to their tool development. Former executives at Applied Materials, the biggest semiconductor tool manufacturer, argue that Sematech had hardly any impact on their business. The organization's biggest success was its effort to coordinate "roadmaps," whereby major chipmakers, tool makers, chip design software firms, and other companies that produced products needed to make chips could coordinate their plans to ensure that each new generation of chipmaking technology had the tools and software needed for mass production.[21]

Ultimately, U.S. chipmakers kept up with Japanese competition in the 1980s by innovating on their technology and their manufacturing processes to keep delivering quality products and low prices. Some Silicon Valley firms were driven out of the market, but others, like Intel, adapted and thrived. Intel succeeded by betting heavily on a new type of chip called a microprocessor, winning the contract to put its microprocessor in the first PC in the early 1980s, thereby guaranteeing the company a central role in producing chips for PCs, which it retains today. In the production of DRAM memory chips, meanwhile, all the legacy firms that suffered from Japanese competition were forced out of the sector. The only U.S. DRAM firm remaining was Micron, an Idaho-based startup that grew despite the competition by finding ways to undercut ultra-efficient Japanese producers on cost. Companies' abilities to find viable business models was more important than any government aid.

U.S. Policy toward Semiconductors in Recent Decades

Since the 1990s, the U.S. government largely has ignored the semiconductor industry. Government continues to fund research into semiconductor R&D through institutions such as the National Science Foundation and DARPA. However, because U.S. chip firms did so well in the 1990s and 2000s—and because most of their international competition came from friendly countries like South Korea or Taiwan—the U.S. government didn't feel compelled to have a semiconductor policy. The U.S. government had an export control policy, which was generally focused on keeping potential adversaries like Russia and China at least two generations behind in chipmaking technology—something that, until recently, was a straightforward task, given the backward state of China's chip industry.

In the 2000s most American officials were focused on helping China become a "responsible stakeholder," in the words of influential diplomat Robert Zoellick, rather than on keeping down China's technological advances. China therefore faced few meaningful limits in its effort to build a domestic chip industry, which had some success during the period. Meanwhile, the shift in fabrication capacity toward East Asia continued just as America's military position in the region was beginning a dangerous decline.

Other Countries' Experience with Industrial Policy

Other countries—including Taiwan, Europe, South Korea, Japan, and, above all, China—have experimented with different types of industrial policy with the aim of building domestic semiconductor industries. Indeed, part of the reason semiconductor fabrication has become concentrated in East Asia is that governments in the region have spent heavily on subsidies to support chipmaking. Some of these industrial policy efforts have targeted support toward specific sectors or firms, while others sought to attract foreign investment. Successful cases all have involved focusing on training and human capital in addition to financial support. Additionally, industrial policy success stories have insisted that recipients of government support prove their competitiveness by selling to global markets. Simply pumping capital into the chip industry is a strategy that occasionally "works" in the short term—if working is defined by an increase in chip output—but never has been a viable long-term strategy to build or bolster a stable semiconductor sector.

The history of other countries' efforts at industrial policy toward semiconductors holds lessons for the United States. First, countries have succeeded when they have focused on helping their firms produce competitive products for global markets. Inward-looking industrial policy almost always has failed. Second, supporting workforce development has been an important part of every successful case study in semiconductor industrial policy. Third, industrial policy has been more effective when it seeks to capitalize on countries' existing strengths and capabilities, playing a catalyzing role. Policymakers seeking to use industrial policy as a cure-all for competitiveness problems will be disappointed. What government can do is nurture a healthy ecosystem for private firms and address security dilemmas (e.g., demand for military systems or diversification away from geopolitically risky suppliers) that markets are ill-placed to handle.

Taiwan and the Creation of TSMC

One of the best examples of industrial policy success is Taiwan's decision to build a chip industry. As early as the 1960s, Taiwanese leaders had decided that attracting plants for outsourcing semiconductor packaging and assembly would be a valuable business for the island. The packaging business at the time required a large quantity of low-skilled labor, which Taiwan had in abundance. Moreover, Taiwan's leaders wanted to intensify commercial connections with the United States and Japan, which they saw as a source of security vis-à-vis the People's Republic of China. They also had the advantage of a sizable number of Taiwanese citizens overseas who worked in the semiconductor industry and could help transfer knowledge.[22]

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Six decades later, Taiwan's semiconductor industry is world-class, and Taiwan's biggest firm, TSMC, is one of the largest publicly traded companies in the world. However, Taiwan's path to playing a central role in the world's chip industry was long and winding. The government first succeeded in the 1960s in attracting offshored assembly and test work, which was low on the value chain but provided a sizable quantity of jobs. Through this offshored assembly work, Taiwan's leaders came to know top U.S. semiconductor executives. For example, when Texas Instruments executives Mark Shepherd and Morris Chang visited Taiwan in 1968 to explore opening a facility there, they met with Taiwan's leading economic officials and regularly stayed in touch afterward. Taiwan, for its part, established a council of foreign technology experts who advised the Taiwanese government on future trends in technology and how Taiwan might capitalize on them.

Taiwan's industrial policy began with an effort to understand the industry and to establish personal connections with the most advanced firms. Later, the Taiwanese government established a research institute, today known as the Industrial Technology Research Institute (ITRI). However, the first major project of ITRI, a project with RCA, had disappointing results. It wasn't until two decades after first attracting offshored assembly plants that Taiwan's government helped found Taiwan Semiconductor Manufacturing Company (TSMC) in 1987. It initially was led by Morris Chang, a longtime Texas Instruments executive whom Taiwanese leaders recruited to help bolster their chip industry. The company was funded largely by the Taiwanese government and by local business leaders who were pushed by the government to invest.

Though Taiwan's government helped TSMC raise funds and granted it highly favorable tax treatment, the company succeeded thanks to its innovative business model and quality manufacturing. At its founding, TSMC was the world's only "foundry," a company devoted to manufacturing chips designed by other companies. At the time, most chips were designed and manufactured by the same firm. TSMC succeeded by convincing customers, largely in the United States, that it could provide quality, reliable manufacturing services. TSMC was the beneficiary of Taiwanese industrial policy, including an artificially undervalued currency, but it succeeded because it correctly identified an unmet market need.

Singapore's Industrial Policy Successes—and Disappointments

Like Taiwan, Singapore has been a hub of semiconductor assembly since the 1960s and today is an important center of chipmaking, including both fabrication, design, and test and assembly. For over half a century, Singapore's government has tried to attract foreign chip firms to the city-state, providing excellent infrastructure, tax breaks, and a highly trained workforce. In some ways, Singapore is a success story in industrial policy, showing how deliberate government action over decades can help build a semiconductor industry. However, Singapore's chip industry has failed to produce a firm that's won an indispensable or highly profitable role in any part of the chip supply chain. Singapore therefore also serves as a cautionary tale, illustrating how even the most capable government bureaucracies can struggle to identify or nurture the most profitable businesses.

Singapore's industrial policy focus on the electronics industry dates to the 1960s, when before independence the city-state established the Industrial Research Unit, which later would give rise to several government organizations that sought to attract and support semiconductor production. In 1968, Singapore attracted its first assembly facility, set up by the U.S. firm National Semiconductor. Within several years, multiple other U.S. and European companies had established plants in Singapore, attracted by the city-state's low-cost and disciplined workforce, as well as low tax rates and clear government subsidies for semiconductors.[23]

In 1983, French chipmaker SGS Thompson established the first fabrication facility in Singapore, providing evidence that its chip industry was moving up the value chain. By the mid-1980s, Singapore made up around 5 percent of the global chip fabrication market. It later diversified into the production of wafers, chip design, and other parts of the chipmaking process.[24]

In 1987, the same year TSMC was founded in Taiwan, the Singaporean government helped establish Chartered Semiconductor. Like TSMC, Chartered intended to provide manufacturing services to chip designers, which at the time was a new and innovative business model. TSMC proved that demand for chipmaking services was immense, turning it into one of Asia's largest companies. Chartered Semiconductor did substantially less well, however, winning only a fraction of the market share of TSMC and thus remaining substantially less profitable than its Taiwanese rival. Chartered eventually was bought in 2009 and merged into U.S.-based Global Foundries.

It is difficult to identify a reason that Singapore's industrial policy was less effective than Taiwan's. Singaporean government officials identified the right industry (foundry fabrication) at the right time. Yet Chartered never managed to keep pace with TSMC, won only a small share of the market, and posted years of losses. Singapore's planners were right to think that the chip market was ripe for a foundry business in 1987, but they failed to realize that most foundry profits would accrue to the leading firm—TSMC. Today, Singapore has a sizable chunk of the world's semiconductor industry, especially for such a small country, but it has none of the industry's most profitable firms.

Europe's Industrial Policy Failures

European firms have played a role in the chip industry since its foundation, but in many cases they have struggled to compete with U.S. rivals, especially for the most profitable segments of the semiconductor market such as chip design. In the early days of the chip industry, major European governments such as Italy, France, and Germany all wanted their own semiconductor manufacturing facilities, imposing tariffs and supporting domestic champions, as well as trying to get U.S. firms to open manufacturing hubs in Europe. This strategy succeeded in attracting chipmaking facilities to Europe, but it also created a fragmented semiconductor sector focused on servicing domestic markets rather than global ones. Because of this, Europe's chip firms were too small and insufficiently focused on the technological frontier. Moreover, because the world's computer industry was centered in the United States, selling to Europe's domestic markets was a strategy for second-class status.

European governments have repeatedly tried to bolster their domestic chip industries, but they often have supported unsuccessful firms while simultaneously distorting incentives and encouraging companies to focus on domestic rather than foreign markets. The two most successful European semiconductor firms today grew primarily thanks to their ability to sell to global markets, not thanks to subsidies at home. In the UK, the government's investments in companies like Inmos, a major project of the late 1970s and early 1980s, failed to create important chip firms. Yet other UK startups did better. Arm, founded in 1990 without any government involvement, created a new business model of licensing its proprietary chip design architecture, which today is used in nearly every mobile device. It is now one of Europe's biggest semiconductor firms, having created a new subsector of the industry where the UK government never had thought of investing.

A similar trend holds in semiconductor manufacturing equipment, which today is a subsector that Europe specializes in. The Netherlands' ASML was spun out of Dutch chipmaker Philips in 1984, once it became clear that semiconductor manufacturing equipment was becoming too complex for chipmakers to build in-house. ASML grew not primarily thanks to support from the Dutch government, though it benefited from a well-educated domestic workforce and investment in R&D infrastructure. The European Union's EUREKA program to support advanced technologies, established in 1985, played almost no role in ASML's success, despite being established around the same time ASML was founded.[25] Instead, ASML succeeded because it immediately won customers internationally, including in the United States and Taiwan, and because it established international partnerships that enabled it to generate the best lithography technology. Industrial policy played a limited role in its success.

Japan's Support for Memory Chip Production: Short-Run Successes, Long-Run Failures

In Japan, industrial policy played an important role in the construction of the country's semiconductor sector. However, the rise and fall of Japan's chip fabrication sector provides a cautionary tale about the limits of industrial policy and cheap capital to support a durable chip industry. Japan entered the semiconductor industry soon after the first integrated circuits were invented, licensing the technology from U.S. firms but heavily restricting the ability of American chipmakers to open fabs in Japan and imposing sizeable tariffs on imports from the United States. Japan also poured cheap capital into its chip firms.

During the early 1980s, Japanese chip firms caught up to U.S. chipmakers in terms of technology level and exceeded Silicon Valley on measures of manufacturing quality. Though U.S. firms complained about government support for R&D in the Japanese chip industry through initiatives like the VLSI Program, this program was small, arguably smaller than what the U.S. government provided in research support, once military R&D via DARPA was included.[26] The primary reason Japanese firms succeeded was their top-notch manufacturing processes and relentless fixation on quality control.

Japanese firms surged ahead of American competitors when measured by market share or output in the 1980s not thanks to Japanese government policy but thanks to the cost of capital. U.S. interest rates shot upward in the early 1980s as the Federal Reserve fought inflation, but Japanese firms benefited from very low interest rates. The structure of Japan's financial system—with tight restrictions on where households could invest funds and a limited welfare state that induced large-scale savings—provided a vast quantity of bank deposits that Japan's banks were eager to lend at low interest rates. Because of this, Japanese chipmakers benefited from cheap loans, enabling them to fight for market share even when it was not profitable to do so.

This strategy worked throughout the 1980s, if "working" is defined by increasing Japan's market share in DRAM chips, the dominant product of that era. However, Japan's competitors, lacking cheap capital, were forced to innovate and to find more profitable markets. U.S. chip firms such as Intel were pushed out of the DRAM market but refocused on more profitable markets like microprocessors. By contrast, Japan's chipmakers succeeded in driving almost all U.S. DRAM producers out of the market, but ended up controlling a sector with substantial overcapacity, so they struggled to make money.

Because of this overextension, Japanese DRAM firms themselves quickly were displaced by lower-cost Korean competitors. Moreover, since most of Japan's chipmakers focused almost exclusively on DRAM chips, they missed several key trends in the chip industry, causing a dramatic decline in Japan's position in the 1990s. Today, Japan remains an important player in certain segments of the semiconductor industry, such as for ultra-pure chemicals and for semiconductor manufacturing equipment. However, it is a much less significant player than in 1980s, in part because its chip industry received so much cheap capital.

China's Vast Semiconductor Subsidies—and Their Mixed Results

The best case study in the difficulties of industrial policy is the country that has been most aggressive in pouring government funds into its chip industry: China. In many ways, China ought to have the best chance of any country to move up the semiconductor value chain. For the past several decades, Chinese leaders have identified semiconductors as a key industrial policy goal. Chinese companies are deeply involved in electronics assembly and so can learn from world leaders in the industry. Moreover, countries like Japan, Taiwan, and Korea—which employed development models somewhat similar to China's—each succeeded in winning a substantial share of the semiconductor industry as their manufacturing sectors grew in complexity. Yet despite substantial support from the Chinese government, China's chipmakers have struggled to catch up to the cutting edge—and when they have succeeded, they often have done so despite the government rather than because of it.

As early as the mid-1950s, the Chinese government identified semiconductor devices as a scientific priority. Peking University and other scientific centers had researchers who were trained at the world's leading centers of semiconductor engineering, including Berkeley, MIT, Harvard, and Purdue. In 1960, China's first semiconductor research institute was established in Beijing, with Chinese engineers producing their first integrated circuit several years thereafter.

Chinese microelectronics lagged until Deng Xiaoping began opening China's sclerotic state sector to private competition and encouraged foreign investment, which during the 1980s and 1990s focused on simple assembly, much like Taiwan and Korea several decades earlier. When the Chinese government tried to domesticate high-value segments of the chip supply chain, it often stumbled. Subsidizing foreigners to open chipmaking facilities in China increased the amount of chip production in the country, but many high-profile deals that were touted as helping China develop domestic capabilities ended up employing large numbers of Chinese workers while keeping critical expertise in the hands of foreign experts.[27]

Doug Fuller, an expert in China's chip industry and the author of *Paper Tigers, Hidden Dragons*, has shown that Chinese chip firms with extensive government involvement tend to struggle to improve their technology, while China's handful of private semiconductor firms with deep international connections have been more successful. China's most advanced foundry, SMIC, functioned mostly like a private firm during the 2000s, when it made real strides in catching up with foreign rivals. One key technique was hiring employees who had previously worked in foreign chipmaking facilities, then encouraging them to train local workers.[28] However, as the Chinese government began to assert a bigger role in SMIC's management, its technological catch-up had stalled, even before the U.S. government began ratcheting up restrictions on the company's access to U.S. technology.

The other prominent success story in the Chinese chip industry is Huawei's chip design arm, HiSilicon. Though Western media coverage has focused on the subsidies Huawei has received from the government, it was far from alone among Chinese firms getting government support. It was far more successful than other Chinese firms, like state-owned ZTE, because it prioritized export and learned to design and sell products to global markets. HiSilicon also learned to design many of the chips used in its devices, including application processors for its smartphones, which are highly complex. HiSilicon very quickly became a leading chip design firm, the only one based in China, before its growth was derailed by U.S. export controls.

Today, China's government is pouring funds into its chip industry, not only through its National Integrated Circuits Fund, but also via related funds organized by provincial and municipal governments. The amount of subsidies flowing into the chip industry is clearly in the tens of billions of dollars, though headlines suggesting hundreds of billions or even trillions of dollars of spending should be taken with a grain of salt. Given the opacity of China's subsidy system, it's unlikely that even the Chinese government knows how much is being spent.

HiSilicon, a fabless semiconductor company wholly owned by Huawei, became competitive in the global marketplace by prioritizing export and selling to global consumers. (Kevin Frayer/ Getty Images)

All this spending will fund a major increase in chipmaking capacity in China, giving China the chance to leap forward in its chipmaking capabilities, if the money is well spent. The scale of government funds Beijing is devoting to its semiconductor sector is unprecedented in the history of the industry. While many of China's state-backed companies have disappointed expectations, and while some of the subsidy-fueled growth has produced scams rather than viable businesses, the quantity of investment alone will guarantee China a larger role in the semiconductor supply chain than it currently occupies. China will develop a broader pool of skilled labor. Subsidized Chinese firms will offer bargain pricing to win market share, even if their technology or profitability lags behind international standards. Chinese industrial policy is inefficient and wasteful, but simultaneously a threat to the market position of existing firms—including America's technological leaders. Because of this, China's semiconductor subsidies present a serious threat to U.S. technological leadership.[29]

China is focusing on the fabrication of logic chips that are not cutting-edge. China also looks likely to win market share in the NAND memory business, thanks to at least $24 billion in state-backed investment (and probably substantially more) that has been provided to YMTC, the leading Chinese firm in that subsector.[30] For all this, however, China still is unlikely to be able to produce cutting-edge logic chips within the next decade, and it may still lag in DRAM memory chips and in many types of analog chips. It also will probably still be importing substantial quantities of U.S., European, and Japanese machine tools for semiconductor production in a decade. China's brute-force industrial policy, pouring in capital without effective mechanisms for selecting successful businesses, is reminiscent of the worst errors of Japan's semiconductor policy in the 1980s. It is not something the United States should try to replicate, even though the major market distortions it creates—and the threats to the viability of U.S. and allied firms—must be addressed.

Market Dynamics and Ramifications for Industrial Policy

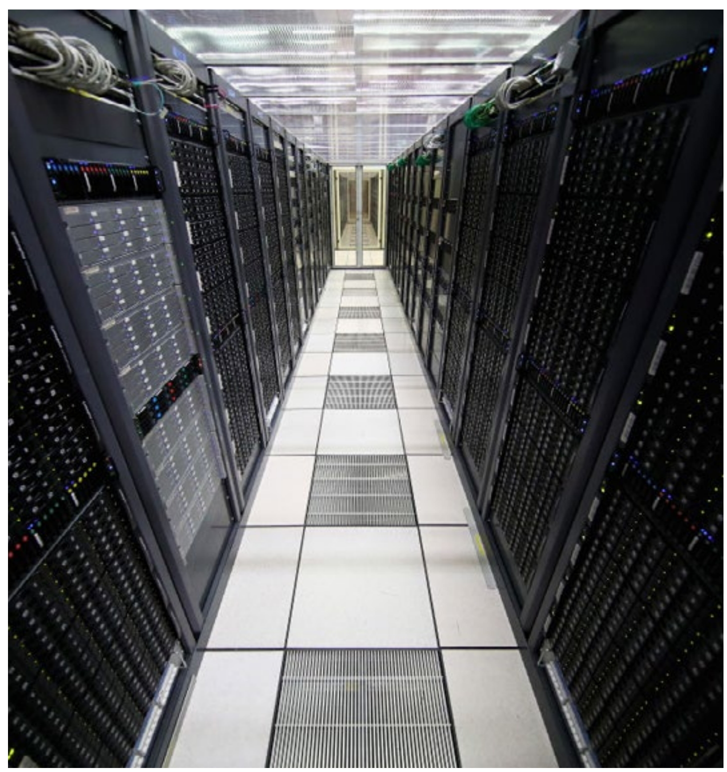
U.S. industrial policy today must consider not only the current structure of the chip industry but also major trends that will reshape it over the coming decade. No industries stand still, but the semiconductor industry changes more rapidly than any other part of the economy, driven by Moore's Law, the prediction that the amount of computing power produced by each chip will grow exponentially. Government programs aimed at present-day dynamics will be out of date by the time they're approved and implemented. The question to ask is not "How can we impact the industry today?" but rather "How can we shape its trajectory over the coming decade?"

Today the semiconductor industry provides chips for three primary end-markets and several smaller ones. Smartphones and PCs consume around 25 percent and 20 percent of all chips sold, respectively, while another 25 percent of chips go into data centers and other IT infrastructure, like phone networks.[31] The remainder of the industry is divided between smaller markets, such as automotive, industrial, and other consumer electronics markets.

Shifts in demand for certain types of chips will benefit certain firms—and certain countries. For example, Intel, which remains one of the industry's biggest firms, was the greatest beneficiary of the growth in PC demand over the past several decades. In the past ten years it also established a dominant role in data centers, though this position now is eroding. Because Intel produces most of its chips in-house, Intel's success in these markets meant that the United States was comparatively self-reliant in PC and data center chips. The deterioration in Intel's competitive position makes the United States more reliant on foreign fabrication, especially in Taiwan. If Intel can successfully launch a foundry business—as it is now trying to do—it might win a share of the business fabricating data center chips designed by big tech firms like Amazon or Google, though it will have to overcome resistance from these competitors in the data center business. For now, a decline in Intel's data center or PC market share implies an increase in reliance on chip fabrication in East Asia, including in Taiwan.

Unlike the PCs and data center end markets, the smartphone segment of the chip industry always has been reliant on fabrication in Taiwan and South Korea. Many key chips in smartphones are designed by U.S. firms such as Qualcomm and Apple (which is one of the world's most advanced chip designers). If Taiwan were to stop producing chips, though, the world's ability to build smartphones temporarily would grind nearly to a halt.

PCs and smartphones are now mature technologies, however, so growth in the semiconductor sector—and potentially, the next set of major chip firms—will emerge from serving other end markets. One growth market is



Cloud computing firms such as Google and Amazon are designing chips specifically for data centers, while semiconductor firms like Intel and Nvidia consider how best to integrate their chips with software in datacenters, such as this data center and server farm in Meyrin, Switzerland, at the European Organization for Nuclear Research (CERN), which is the world's largest particle physics laboratory. (Dean Mouhtaropoulos/Getty Images) in data centers and other high-performance computing applications. Companies like America's Nvidia have grown by producing chips that are tailor-made to run artificial intelligence (AI) algorithms. Many other firms, from established chipmakers such as AMD and Intel to AI-focused chip startups, are trying to win market share in data centers. Meeting this demand will play to America's strength in chip design and the fact that the biggest potential customers, major cloud computing and big tech firms, are largely U.S.-based. However, except for Intel, most firms designing data center chips outsource production to Taiwan or South Korea, potentially increasing U.S. vulnerabilities to geopolitical crises.

A second major growth market for semiconductors is the automobile sector. Cars have used semiconductors for many decades, but both the quantity and the sophistication of chips in cars are growing. Today, a typical car has many simple chips for managing features from fuel injection to power seating to airbags. As more features are added to cars, more of these simple chips will be needed. More significant, though, is that autonomous driving systems require high volumes of highly advanced processor chips, powerful memory chips, and complicated semiconductor-based sensors, a trend rapidly increasing the number and the value of semiconductors in new cars. Finally, electric vehicles require specialized semiconductors to manage their power supply.

U.S. firms already are major players in auto semiconductors. Tesla, for example, already is a sophisticated chip designer in its own right. Intel's Mobileye division, meanwhile, produces chips and software for autonomous driving systems. While China has signaled that it plans to support its domestic semiconductor industry focused on electric vehicles and the auto sector more generally, multiple firms are vying for market share, and many of the leaders currently are in the United States or Europe.

In addition to changing end markets, the way the semiconductor industry packages chips is changing. New technologies to package chips together are enabling the rise of "chiplets"—multiple chips, packaged together, that can be mixed-and-matched to provide the best combination of computing power, memory, and cost for every use. All the industry's big players are experimenting with advanced packaging technologies and—no less importantly—testing whether the ability to package more diverse sets of chips will enable new business models in the industry. The results are not yet clear, but many industry analysts expect that rising use of chiplets could upend some semiconductor firms' business models.

Finally, many semiconductor firms are thinking more seriously than ever about how their chips interact with the software that will run on them. Some chip firms have long considered their chips' interaction with specific software, while others have sought to sell "general purpose" semiconductors that can interact efficiently with many different programs. As data centers grow in importance, some big cloud computing firms like Amazon and Google now are designing chips specifically for the use cases in their data centers. Companies like Intel and Nvidia, which sell chips for data centers, are thinking not only about their silicon hardware, but also integration with the software they run. This type of "systems integration" thinking is likely to grow in importance, especially in the data center business.

Predicting the evolution of these and other industry trends is not something that governments have a track record of doing well. When it comes to science and engineering challenges, parts of the government such as DARPA regularly have identified technical barriers to progress and funded research programs around them. Assessing which business models will take off, however, is a very different challenge. Industrial policy has worked best in countries that lag behind the technological cutting edge and are trying to catch up by following a path set by others. For the United States, on the technological frontier of the chip industry, government will struggle to predict the evolution of industry better than the private sector. This presents a dilemma for policymakers, who must develop a view of the industry's future to identify risks but also must expect that their knowledge will lag behind private firms. To be effective, government should set its goals around shaping broad, long-term trends, rather than rescuing specific firms or developing certain capabilities.

Implications for Industrial Policy toward the Semiconductor Industry

The U.S. government should focus policy toward the semiconductor industry around four main objectives: promoting technological advances, guaranteeing security of semiconductor supply, retaining control of choke points, and slowing China's technological advances.

Promoting Technological Advances

The United States consumes around a quarter of the chips produced each year, so it is as reliant as any country on the success of "Moore's Law," the dictum that the computing power on a chip should increase at an exponential rate.[32] Ensuring that technological advances continue is crucial to the health of many U.S. industries and, ultimately, the entire American economy. Most of the infrastructure needed to continue Moore's Law already is in place. The chip industry spends proportionally more on R&D than any other industry except pharmaceuticals. Though the cost of chipmaking is rising, new packaging techniques will provide further performance improvements.

Moreover, venture capital has flowed into new chip design businesses, especially for chips intended to support AI workloads, a trend that promises to bring down the cost of chips for AI. Basic and early-stage applied research into both trends has been funded by U.S. government institutions such as the National Science Foundation and DARPA, which launched a new Electronics Resurgence Initiative in 2017 to boost its funding in this sphere.

To intensify these efforts, policymakers should:

Invest in workforce development and ensure the world's leading chip experts can work in the United States.

Companies repeatedly cite workforce issues as a key challenge in the U.S. semiconductor industry. Government can do more to support career pipelines in the semiconductor sector, ensuring that highly qualified students see viable career paths in the chip industry.[33] One model is Purdue University's recent launch of a specialized program in semiconductor engineering, in close partnership with industry.[34]

In addition, facilitating work visas for foreign experts in semiconductor-related technology also would help. Foreign experts have been at the core of Silicon Valley since the days of Fairchild Semiconductor, in which two of the eight founders were born outside of the United States, while some of the key research on semiconductor technologies at Bell Labs was conducted by immigrants from countries such as Egypt and Korea. Concerns about the potential impact of Chinese talent programs in transferring expertise are likely overblown, especially given that Chinese chip firms regularly hire Japanese, Korean, Taiwanese, and U.S. citizens to develop their industry alongside Chinese nationals. Instead, to prevent leakage of human capital to China, the United States should strengthen legislation protecting trade secrets in the semiconductor industry and encourage more restrictive non-compete agreements that limit employees of the U.S. chip industry from working for Chinese firms.

Focus new funding not on basic research, but on technology development and prototyping.

An idea can win a Nobel Prize, but it takes a commercial product to build a business. In the semiconductor industry, the transition from "idea" to "product" can be prohibitively expensive. Though universities have a highly effective lobbying apparatus in Washington that directs funds toward basic research, increased support for prototypes and commercialization would be more impactful in supporting industry. This is one lesson from the early days of the chip industry, when pioneers like Bob Noyce avoided government R&D contracts but relied on the military to provide the initial market for his first chips, which were high-cost and had small production runs.

In the past, institutions such as Bell Labs, the in-house research facility at AT&T, played a key role in carrying promising technologies forward to commercialization. Bell Labs was a unique organization because it was positioned within a company, AT&T, that because of its monopoly status was both highly profitable and de facto prohibited from entering new business. Though these unique circumstances don't exist today, Bell Labs produced many of the key innovations, from information theory to deposition equipment, that undergird contemporary information technology. The U.S. government can't replicate Bell Labs, but Congress and the administration should focus research funding on institutions that sit at the intersection of science and industry, which are more likely to produce new useful technology than universities or basic R&D.

Guaranteeing Resilience and Integrity of Supply

The chip industry has an excellent record of delivering substantial supply of chips during peacetime. Natural disasters like the 1999 Taiwan earthquake or 2011 Japan tsunami caused only minor disruptions. Despite the well-publicized shortage of auto chips over the past two years, the chip industry dramatically increased output during the COVID pandemic, shipping nearly 8 percent more chips in 2020 and 20 percent more chips in 2021. The "shortage" of chips during the pandemic was not caused by the industry's failure to produce more, but by a vast and unexpected surge in demand, particularly in the auto sector, where firms canceled orders in the pandemic's early days only to find that demand for their cars recovered quickly. However, chipmakers already had reallocated their manufacturing capacity to other customers. The "semiconductor supply chain crisis" was mostly an "auto supply chain crisis"—and it was mostly the automakers' fault.

Legacy chips are crucial for U.S. defense production. Earlier in 2022, there was difficulty in ramping up the production of antitank Javelin missiles due to shortages in legacy chips. In May 2022, a Ukrainian soldier uses a U.S.-manufactured Javelin missile. (John Moore/Getty Images)

While the chip industry has an impressive record of resilience during peacetime, the concentration of fabrication and assembly in East Asia creates massive vulnerabilities to geopolitical pressure. Market forces—and East Asian governments' subsidies—have attracted more of the industry to that region, but short-term economic interests and national security imperatives are not aligned. Some level of industrial policy is needed to avoid excessive vulnerability to geopolitically induced supply disruptions, both for the supply of chips for defense purposes as well as broader supply for the economy at large.

Assuring the supply of legacy chips for defense systems presents a unique set of challenges. Weapons systems often last for decades—far longer than an iPhone and PC is in service—and therefore have a unique demand for legacy chips. One challenge for defense procurement is keeping production online long after the commercial viability of older chips has disappeared. For example, when Raytheon was asked to increase the production of Javelin antitank missiles this year to replenish supplies sent to Ukraine, it discovered it could not quickly ramp up production of the necessary microelectronics.[35] Keeping legacy semiconductor production available for defense production is expensive but necessary for many types of military equipment.[36]

What role is there for industrial policy in the over 95 percent of semiconductors that are not used for defense purposes? Some analysts suggest focusing on semiconductors in "critical infrastructure," but most of the chips we use are critical. Some of the biggest use cases of chips are in data centers, PCs, and smartphones—devices that are all critical in modern society. If the operation of Apple's smartphone processors or Intel's PC processors were disrupted, the economic impact could be disastrous. Even the simple chips that manage fuel injection into car engines are critical. There aren't many semiconductors that don't qualify as critical. The uncomfortable reality is that the entire industry is fundamental to the normal operation of our economy and society. Industrial policy therefore must deal with the chip industry as a whole, rather than with small segments of it.

In addition to assuring the supply of chips to defense and commercial markets, the U.S. government also must ensure the integrity of chips integrated into sensitive systems. The Defense Department requires high confidence that the chips it uses in military systems have not been compromised in their design, fabrication, or assembly phases. Though the number of known security incidents involving semiconductors is far lower than in software, chip design flaws such as Spectre and Meltdown, which compromised encrypted data, also have been discovered. Adversaries could modify chip designs or production processes to compromise chips by accessing fabrication or packaging activities. Alternatively, adversaries could modify chip designs, which would not require physical access to a facility. There is some increased risk of sabotage when producing defense chips in offshore facilities relative to domestic facilities, though substantial research is underway on mechanisms to verify that chips have not been modified or sabotaged.[37]

To guarantee resiliency and integrity of semiconductor supply in U.S. market, policymakers should:

Invest in techniques to identify semiconductor security flaws.

Though semiconductors have had fewer demonstrated security flaws than software, the United States lacks sufficient tools to assess whether chip designs have been modified or whether chips have been tampered with during fabrication or packaging. More funds should be devoted to developing methods for verifying the security of chips, whether these chips are used for civilian or military purposes.

Build additional semiconductor expertise in the U.S. government.

The chip industry's supply chain is one of the world's most complex and international. Understanding how the supply chain functions is crucial to making effective policy toward the industry. Though parts of the U.S. government, including the Commerce Department and the Defense Department, have existing knowledge about the industry, the United States should invest in a dedicated unit, potentially in the Commerce Department or the International Trade Administration, to track shifts in supply chains and in technological trends, providing granular analysis to the Executive Branch and to Congress.

Identify and mitigate supply chain dependence on adversaries.

Most of the semiconductor supply chain involves materials, designs, and machinery from countries that are allies or partners of the United States, though China's growing role in the semiconductor industry is changing this. The United States should regularly examine the supply chain to identify areas of dependence on geopolitical adversaries. For example, Russia has restricted exports of noble gases in an attempt to cause problems in chip manufacturing. Once identified, points of dependence on adversaries should be mitigated, if necessary by government funding for domestic production or stockpiling, and/or restrictions on purchases from Chinese or Russian firms.

Diversify the fabrication base via subsidies and by pressuring TSMC and Samsung to build more advanced facilities in other geographies.

To secure the semiconductor supply in case of war in East Asia, more fabrication and assembly facilities must be built in other regions. First, the U.S. Congress should continue to monitor the cost gap between building a fab in the United States versus in East Asia, recognizing that the tax benefits in the CHIPS and Science Act may not be enough. Regulatory and environmental rules also drive up the cost of American domestic chip fabrication. Second, TSMC and Samsung, the two firms producing leading edge logic chips, should be pressed to further diversify their production base. Samsung has announced a new facility in Texas, while TSMC is building fabs in Japan, Arizona, and Singapore. However, most of these firms' new production capacity and all their advanced technology development remains in their home countries. U.S. officials should replace vague talk about "friendshoring" with a policy of pressing these firms to continue diversifying their fabrication base, including by rolling out new technology nodes simultaneously in their home countries and in the United States.

Retaining Control of "Choke Points"

Certain U.S. chipmakers, equipment manufacturers, and chip design software firms play a practically irreplaceable role in semiconductor supply chains. Policy toward the semiconductor industry should seek to nurture these choke point firms. The U.S. government has used its control over choke points against rival governments like Russia and China. Because U.S. firms and U.S.-originated technology play a crucial role in semiconductor manufacturing equipment and in chip design software, prohibiting access to this technology effectively prevents the manufacture of advanced semiconductors.

The challenge with choke points is that cutting them off increases other countries' incentive to find a way around them. The best way to nurture a choke point is never to use it, but such a policy would defeat the point of cultivating choke points in the first place.

To nurture choke point firms, the United States should:

Prioritize R&D support around choke points.

Retaining technological choke points is an important foreign policy goal, so government research funds should focus on innovations that deepen U.S. control over choke points. After identifying such strategic technologies, the Department of Commerce should devise programs to support R&D that sustains U.S. innovation in these spheres. In the semiconductor manufacturing equipment sector, one challenge is that startups and university researchers struggle to acquire access to expensive equipment needed to test new concepts. In the past, DARPA funded programs to give universities access to advanced chipmaking capabilities. The Commerce Department should provide funds to semiconductor manufacturing equipment manufacturers to make their advanced tools available to U.S. startups and academic researchers, sustaining U.S. capabilities in this sphere.

Alongside allies, deepen export controls around manufacturing equipment.

If choke points are overused, other countries' incentives to innovate around them increase. When the United States aligns its export controls with allies, the difficulty for China in finding alternatives increases. The United States should devote more diplomatic capital to ensuring that allies in Europe and Asia have aligned their export controls around choke points. In addition, the administration should deepen consultations with allies about supply chain mapping, to include mapping major component parts in semiconductor manufacturing equipment and assessing whether export controls also should be applied to critical components.

Retaining America's Technological Advantage versus China

The ability to design and fabricate advanced semiconductors has profound economic and military importance. Chips and the miniaturized computing power they enable have played a foundational role in U.S. military power for more than half a century. While Russia lags far behind the United States in the semiconductor space, China has improved its capabilities rapidly over the past two decades. Moreover, the Chinese government is investing heavily to build chipmaking capacity. Unlike previously, the United States now must adopt strategies to widen the technological gap between the United States and its allies, and China to adapt to Beijing's enormous subsidies and its intensifying efforts to domesticate a larger share of the semiconductor supply chain.

Offer China a deal to limit chip subsidy schemes.

A central challenge confronting the U.S. chip industry today is the massive Chinese government subsidies that let Chinese firms undercut foreign rivals. Existing bodies such as the World Trade Organization lack the tools to address these subsidies, in part because China often funnels subsidies via investment funds that are ostensibly private but are actually controlled by Beijing. The United States and allies should offer China a new agreement on semiconductors, whereby the United States agrees not to intensify restrictions on Chinese chip firms if Beijing credibly halts all its implicit and explicit subsidies for the chip industry—whether at the local, provincial, or national levels—while providing intrusive inspection and data sharing provisions to verify compliance. China is unlikely to agree to such a deal, but offering it would help clarify to allies that China's challenge can't be addressed within existing frameworks and therefore requires new, more restrictive measures.

Limit foreign investment in China's chip industry through outbound investment controls, ideally coordinated with allies.

A system of targeted outbound investment controls should be employed to ensure that U.S. firms and venture capital are not supporting the Chinese chip industry. First, the United States should work with allies to halt their firms from establishing new design, fabrication, or assembly facilities in China. Given China's expansive efforts to pressure firms to transfer technology and expertise, the financial benefits of investment onshore simply aren't worth the risk. In the past, China has strong-armed foreign firms into establishing facilities in China, so an outbound investment regime would give firms more negotiating power vis-à-vis Beijing. Second, outbound investment screening should monitor venture capital funding into China-based startups, prohibiting investments that involve transfer of expertise in cutting-edge subsectors.

Intensify export controls in coordination with allies.

As long as the United States and allies retain a durable technological lead over adversaries, export controls will be an important tool to restrain adversaries' advances. Controlling the transfer of certain types of chips to

Allied measures such as coordinated export controls and sanctions between G7 nations—foreign ministers of which are gathered here in December 2021—are much more effective than unilateral measures in retaining a technological lead over adversarial nations. (Phil Noble/WPA Pool/Getty Images).

China is unlikely to have a major impact given the ease of buying most types of chips second-hand. Attempting to limit transfers to military end-users is a worthwhile effort, though enforcement inevitably will be spotty. Nevertheless, even partially disrupting the Chinese military's semiconductor supply chain may induce them to use less advanced chips produced at home, causing them to field less capable military equipment.

The administration should devote more focus to tightening export controls on semiconductor manufacturing equipment and software, providing more funding and oversight for the Commerce Department's Bureau of Industry and Security to enforce tighter controls. It is not realistic to impose export controls on equipment for making logic chips above 14 nanometers, given the availability of alternative sources, but the United States should work with allies to strictly limit transfers of more advanced equipment. The United States should be prepared to keep these controls in place even as technology advances. The prior policy of keeping rivals two generations behind the leading technology level provides an insufficient gap given China's capabilities and ambitions.

Address Chinese chip subsidies via sanctions and export controls, coordinated with allies.

As China pours subsidies into its chip industry, its firms will gain market share in some segments because they do not need to consider profitability. Heavily subsidized Chinese firms should be stopped from breaking into new and important markets. For example, China's YMTC may be approaching commercially viable NAND memory chips, thanks to many billions of dollars of subsidized government funding. Apple reportedly is considering buying chips from YMTC, for example.[38]

Alongside allies like Japan and South Korea, whose firms also are threatened by YMTC's state-subsidy driven strategy, the United States should prepare to restrict the firm's ability to seize market share by applying export controls and sanctions. This could include secondary sanctions that limit firms in other countries from transacting with the company. This would be a controversial move among allies, but secondary sanctions may be needed to have a sufficient impact. Moreover, given the extensive state support YMTC has received—and the repeated inability of legal strategies via international trade agreements to restrain Chinese subsidies—export controls should be used to limit this firm's ability to expand its market share.

Conclusion

Semiconductors have played a major role in sustaining American power since the first integrated circuits emerged out of the Cold War arms race. Today, governments around the world, from Japan to South Korea to Europe and—especially—China are pouring funds into the development of their chip industries. Alongside technological trends and shifting business models, the future of the industry will be shaped by government policies, too.

The U.S. government is just beginning to wake up to the need to devise a coherent strategy to approach the semiconductor industry. The history of industrial policy suggests that government can play a productive role in supporting workforce development and in funding R&D and prototyping. Moreover, the government has a clear role to play in addressing the security challenges posed by the excessive concentration of the industry's fabrication and assembly capability in and around China, which presents an acute risk of disruption in case of geopolitical crisis. To start, however, the U.S. government must deepen its expertise in the industry to ensure policymakers understand the complex supply chains that undergird the semiconductor industry and produce the computing power that U.S. prosperity and security depend on.

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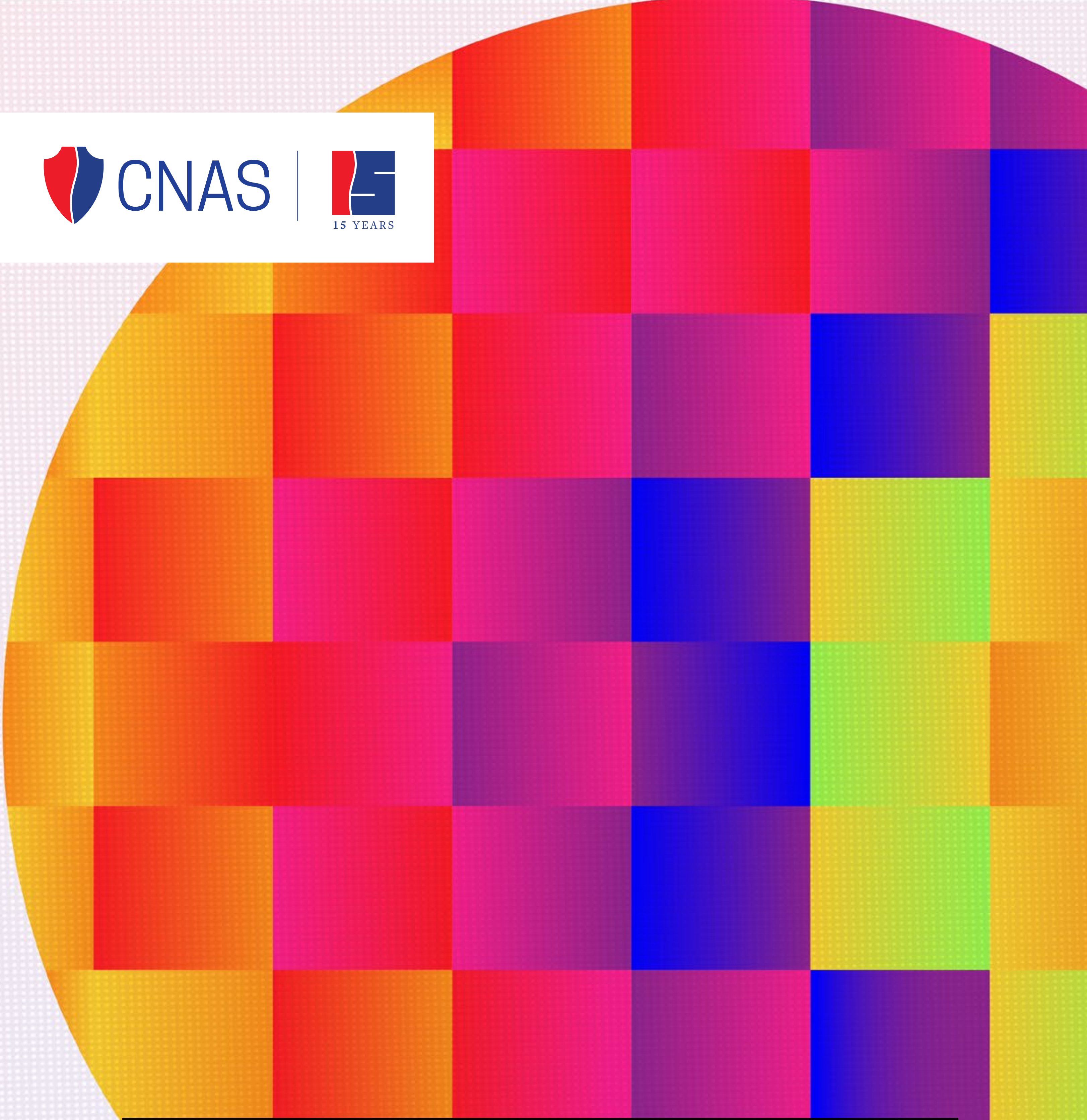

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Chris Miller