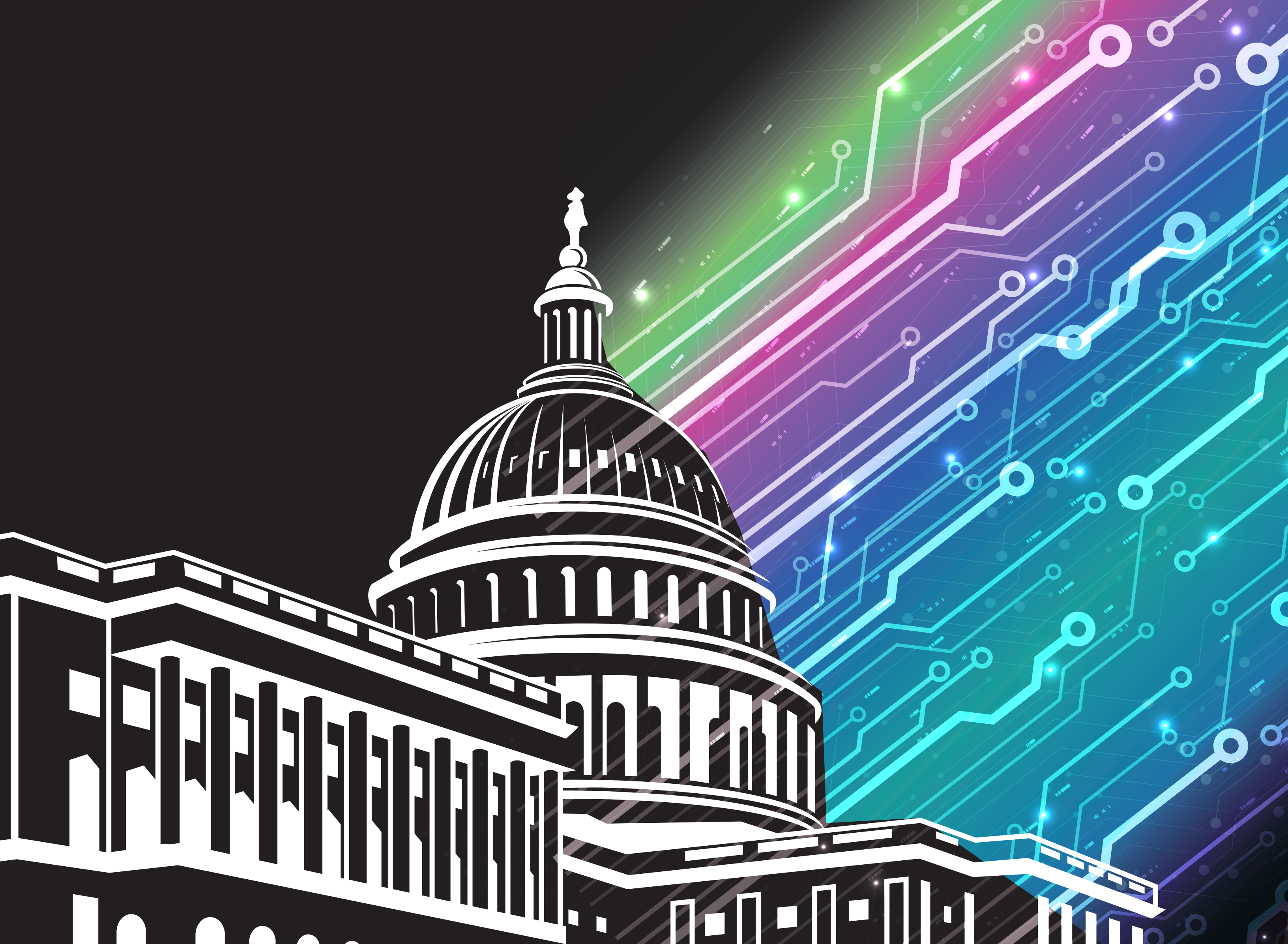
FOREIGN POLICY RESEARCH INSTITUTE

LABS OVER FABS

HOW THE U.S. SHOULD INVEST IN THE FUTURE OF SEMICONDUCTORS



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FOREIGN POLICY RESEARCH INSTITUTE

A nation must think before it acts

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CONTENTS

EXCECUTIVE SUMMARY

The U.S. semiconductor industry faces an existential competitive threat. China's efforts to catch up and eventually overtake the U.S. in semiconductor technology is not only an economic challenge—it is also a security threat. The Trump administration's decision to pressure Huawei by cutting off its access to critical semiconductor technologies has only intensified China's commitment to developing its own ability to design and manufacture computer chips without reliance on foreigners. China has spent billions of dollars in state subsidies, and plans to spend billions more in the coming years. At risk is not just the U.S. industrial base, but also the complex supply chains that link U.S. firms to customers and suppliers in South Korea, Taiwan, Japan, and several European countries.

On February 24, 2021, President Biden ordered a 100-day review aimed at "securing America's critical supply chains." The executive order focused on the semiconductor industry, declaring that "over the years we have underinvested in production—hurting our innovative edge—while other countries have learned from our example and increased their investments in the industry."

While production certainly has its place, it would be dangerous for the U.S. to focus solely on the fabrication of semiconductors at the expense of other parts of the chip production process—including design, software, and production machinery—where the U.S. is currently stronger. There is a case to be made for supporting the construction of manufacturing facilities ("fabs") for certain types of specialized chips, such as those needed in the defense sector. But reshoring most or all production is not a realistic goal. Moreover, the tens of billions of dollars that such a policy would cost are better spent elsewhere.

Beyond that, the U.S. should focus less on supporting production of today's technologies, which given the pace of innovation will soon be out of date. Instead, scarce resources should be devoted to shoring up the broader semiconductor ecosystem on which American innovation depends. In the past, the government has played a major role in investing in research that is not yet commercially viable, something it should be doing more of today. It should build talent pipelines from high schools to universities to corporations and startups, ensuring an ample supply of semiconductor engineers. And the U.S. should see open-source chip architectures such as RISC-V not as a threat to existing intellectual property, but as a technology that could unlock a new wave of semiconductor innovation—something that the U.S. would be well placed to lead.

POLICY RECOMMENDATIONS

1. PUSHING THE BOUNDARIES OF CHIPS

- The U.S. should create or reinforce 25 university-industry centers of excellence in semiconductors with a heavy emphasis on cutting-edge research and development.

2. MAKING CHIP CAREERS COMPETITIVE

- The federal government in tandem with state and local school authorities should sponsor high school centers of hardware excellence that can offer students spaces to experiment, explore, learn and build in chip and hardware fields.

- The United States government should fund a national talent program for 5,000 undergraduates and 1,000 graduate students per year to cover full tuition and annual stipends for an academically selective corps of next-generation semiconductor researchers, scholars and professionals (the CHIPS Fellowship Program — Creative and High-tech Innovation Professionals in Semiconductors).

- Similar to the NSF CAREER Award for early-stage research professionals, the government should expand funding for scholars across a diverse range of semiconductor-related fields pursuing projects at the cutting-edge of this field.

3. OPENING AMERICAN SEMICONDUCTORS

- As part of its supply-chain resilience initiatives, the Defense Department should mandate that open standards be used throughout its supply chains wherever feasible.

- Through NIST and other standards-setting agencies, the U.S. should spearhead global initiatives alongside its allies to define and standardize new open-source models for semiconductors and the software built on top of them.

INTROD

UCTION

Concerns about America's strength in semiconductors have reached a fever pitch as the country's leadership in this critical technology has declined. It's not hard to understand why: America was dominant in the industry it invented from the 1950s to 1970s, ushering in today's digital economy. Today, however, though American firms still lead in the design of chips, manufacturing is largely outsourced to Taiwan and South Korea. Manufacturing chips is extraordinarily complex and high value. American chip designers don't offshore to Asian producers because they are low cost—they work with Taiwanese and South Korean firms because these are the world's only companies that have mastered the ultra-advanced manufacturing processes needed to make leading edge logic chips.[1]

There are two main concerns, one focused on America's inability to manufacture leading-edge chips, the other on emerging challenges to America's currently dominant position in chip design. Start with manufacturing, often called "fabrication" in the chip industry. The United States manufactured only 12% of the world's chips in 2020. In recent years, America's most advanced chip manufacturer, Intel, has fallen behind Taiwan Semiconductor Manufacturing Corporation (TSMC) and South Korea's Samsung in terms of the precision of their manufacturing processes. The smallest, fastest logic chips can now only be manufactured offshore. America's lead in chip design, meanwhile, has been challenged by firms in the United Kingdom, Taiwan, and the People's Republic of China. The only producer of the most advanced extreme-ultraviolet lithography machines that are needed to produce chips is based in the Netherlands. It is easy to see why defense supply chain experts worry the United

1 Semiconductors are generally divided into three categories: logic (eg, smartphone, PC, or server chips); memory; or analog (eg, sensors). Taiwan's TSMC and South Korea's Samsung have a lead in the fabrication of logic chips, though U.S. firms produce at the leading edge in memory and analog.

States faces risks over access to many of these critical components.

China under General Secretary Xi Jinping has worked to make itself a semiconductor leader by trying to subsidize its way to the top. Beijing's *Made in China 2025* industrial strategy targeted semiconductors as a priority technology. In line with that blueprint, the country has used multiple state subsidy programs to invest billions of dollars into its chip effort. Though these programs have faced major challenges—not least because of new U.S. export controls—most industry observers believe that China is likely to gain market share, especially in the design and manufacturing of chips. China currently imports over $300 billion of chips per year, a trade volume greater than even China's purchases of oil. Like the United States, China mostly buys chips produced in Taiwan or South Korea, though many are designed by American companies in the U.S. Beijing's strategic objective is to replace foreign design and production with Chinese chip firms.

Fears that the U.S. will lose its position in chip design—and the reality that it is no longer a leader in chip manufacturing—have triggered discussion among U.S. policymakers that the domestic semiconductor industry needs help—and fast. The past several years have seen a bevy of proposals from policymakers, researchers, and the chip industry, ranging from tens of billions of dollars of new subsidies to further trade restrictions to new export controls and sanctions on Chinese competitors.

Many of these proposals define America's chip challenges far too narrowly; they are focused on resuscitating the past glory of the industry rather than investing in areas where America can lead the future. Moreover, they are often designed to close the industry off to competitors rather than advocating open competition—and ensuring America is the most competitive player.

First, much discussion about investing in chips has focused on ensuring the dominance of the United States in designing and resuscitating U.S. manufacturing of "leading edge" chips—chips that use the best manufacturing process in fabrication. Yet, there isn't one leading edge, but rather many different edges. Consider different types of chips. Some are digital, providing the computing power in servers and iPhones. Others are analog, such as those managing the power supply in devices. Chips are devised using different instruction set architectures, with PCs and most data centers running on the x86 architecture while UK chip designer Arm's architecture is mainly used on mobile devices.

Chips that power data centers can cost thousands of dollars, while the simplest microcontrollers can cost pennies. Some chips, including many types of memory chips, can be plugged into different devices. Others, like those designed by Tesla, only work in the company's cars. Then, there are burgeoning frontiers like quantum computing that use entirely different properties to construct a new model of computer processing. Rather than designing a policy for one "leading edge," defined solely by the manufacturing of logic chips, policymakers need to see the semiconductor industry as a diverse collection of different technologies, each with key uses in the economy. America's strategy should be to support a deep and resilient chip ecosystem encompassing many different areas of the industry.

This ecosystem-based perspective is absent from most policy discussions around semiconductors, where a focus on market interventions like business incentives and trade restrictions have dominated the discussion. Yet, America's leading position in semiconductors starts with its educational and research institutions and, by extension, the high skill of its workforce. A more strategic and comprehensive plan for semiconductors must look broadly at the industry as a whole and ensure that the diverse talent and research required for sustaining America's competitive advantages are fully supported.

Third, the semiconductor industry is going through a generational transition from closed-source technologies to open-source models, which will empower a more diverse, specialized, and competitive chip industry. U.S. policymakers have been divided over this transition, with widespread fear that open-source technology will surrender America's competitive advantages. Open-source will force some chip firms to change their business models. But if approached strategically it could also catalyze a new generation of semiconductor innovation. Rather than trying to defend incumbents who fear open-source technologies and who are trying to defend existing intellectual property, the U.S. should ask how it can encourage adoption of open-source chip architectures to drive down cost, increase security, and catalyze innovation.

America's actions to support its semiconductor industry need to focus not on protecting the present-day leaders but on fostering a base of innovation that will springboard future leaders. This report explores three ways the U.S. can design a more comprehensive policy for the semiconductor industry by

- Supporting next-generation research into semiconductor technology
- Improving the pipeline of engineers and talent into the semiconductor industry at all phases
- Embracing open-source technologies to make America's industry the most globally competitive

FOCUS ON NEXT GENER

1

RATION TECHNOLOGIES

How can the U.S. government support next generation semiconductor technologies? Competitors from South Korea, Taiwan, and—increasingly—China have taken market share in the manufacturing of chips. Some analysts have suggested that the U.S. market position is under threat. The U.S. government is now mobilizing to support the microelectronics industry. China's self-sufficiency drive is something new—and worrisome—for the chip industry, but this isn't the first time that the United States has faced a challenge for the dominant position in the global chip industry. This section will explore how the U.S. semiconductor sector faced international competition in the past, notably from Japanese rivals in the 1980s. The strategies that were successful then in retaining industry leadership hold lessons for today. Now that the U.S. government again considers semiconductors as a strategic technology, the industry's history provides useful templates for assessing efforts to support chip technology.

FROM JAPANESE COMPETITION IN THE 1980S TO CHINESE COMPETITION IN THE 2020S

In recent years, China's government has launched multiple initiatives to catch up in semiconductor technology. It is pouring billions of dollars annually into its chip firms. Programs like *Made in China 2025* identified microelectronics as a priority industry for reducing China's foreign reliance. According to the Organization for Economic Co-operation and Development (OECD) studies, China provides substantially higher subsidies than any other country.[2] The Trump Administration struck back against China's chip efforts by imposing export controls that prevent Huawei and its HiSilicon chip design unit from contracting with almost any chip manufacturer to produce its chips. In addition, the U.S. has restricted SMIC, China's biggest manufacturer of

2 "Measuring distortions in international markets: The semiconductor value chain," Organisation for Economic Co-operation and Development, December 12, 2019, https://www.oecd-ilibrary.org/trade/measuring-distortions-in-international-markets_8fe4491d-en.

chips, from buying advanced equipment from abroad. In response, Beijing has redoubled efforts to subsidize domestic chip production and design. Most studies expect China's share of the semiconductor manufacturing sector to increase over the coming decade, though China currently can't produce the most advanced chips with the smallest feature sizes and is unlikely to do so in coming years.

Yet today's competition with China isn't the first time that the United States has faced existential competitive threats. In the 1980s, Japanese companies learned to produce DRAM memory chips—which at the time were the mainstay of the semiconductor market—at higher quality and lower price than American companies. Japanese firms first drew on practices pioneered by U.S. chip producers, but improved them substantially, driving down the rate of manufacturing defects. U.S. chip companies cried foul, accusing Japan's government of subsidizing semiconductor production and stealing U.S. chip secrets. There were credible instances of Japan doing both, but it was undeniable that U.S. firms lagged Japan in quality—which American customers pointed out when choosing to buy Japanese products.

U.S. chip firms in the 1980s demanded government subsidies and the imposition of restrictions on Japanese imports. After intense lobbying by semiconductor executives, they got both, convincing even the generally free-market Reagan administration to support protectionist measures to help the industry. Armed with the threat of tariffs, the Reagan administration forced Japan to adopt quotas and price floors for DRAMs and EPROMs, two types of memory chips. But in hindsight, it isn't obvious that those actions made much difference. All but one American DRAM producer either refocused on other markets or went bankrupt.[3] Indeed, cutthroat competition in the DRAM market eventually drove all the Japanese firms out of the market, as they were supplanted by even lower-cost rivals from South Korea as well as by Micron, an innovative new U.S. firm that through innovation managed to produce DRAM chips far more cheaply than American firms previously had.

Protectionist policies were designed to support American manufacturing of products that already existed. But Moore's Law made that impossible. A prediction coined by Intel co-founder Gordon Moore, Moore's Law states that the computing power of chips will double every two years. Because of this rapid technological change, the most advanced semiconductors are often out of date in just a couple of years.[4] Japanese firms, which had a lock on the DRAM market in the 1980s, found themselves facing

3 The exception is Micron, which was then a startup that undercut its American rivals on cost and quality.

4 The classic work on disruptive innovation is Clayton Christensen, *The Innovators' Dilemma* (Harper Business Reprint, 2011).

huge problems by the early 1990s. They were out-innovated by American rivals like Intel. Their strategy of borrowing huge sums to build fabs—reminiscent of China's state support today—caused massive overexpansion that dragged down Japanese firms in the 1990s when loans came due. And the focus on existing technologies left Japan vulnerable to new competitors from South Korea, which soon learned how to produce DRAM as efficiently and at even lower cost. Today, Japan remains a major player in certain parts of the semiconductor supply chain, but it is far from the seemingly dominant role of the late 1980s.

The U.S. chip industry fended off the Japanese challenge not thanks to protectionism, but innovation. Two examples demonstrate this: Intel's pivot away from DRAM and the origins of electronic design automation (EDA) tools. Start with Intel, which was one of America's leading DRAM producers in the early 1980s. It suffered immensely from competitive Japanese products that were low cost and high quality. Rather than trying to compete head-on, Intel left the memory market and reoriented its business model toward high-value chips, winning the earliest contract to produce chips for the IBM personal computer. Instead of relying on government subsidies or protectionist policies, Intel pivoted its business, drawing on America's existing pool of chip experts, deep capital markets, and a business culture that prioritized innovation over defending incumbent producers.

This pivot made Intel the world's leading provider of PC chips, earning it rich profits as PCs became mainstream in the 1990s and 2000s. It was the world's largest chip firm for much of the period. By contrast, U.S. firms that stayed in the DRAM business and prayed that protectionism would save them were forced out of the industry. Those that invented new products and new business models did better. What made Intel so successful was that it identified a high-margin part of the market and in tandem with Microsoft, which built the software on which PCs run, built an ecosystem around it. The innovation in Intel's business model was as important as the innovation in its research labs.

THE U.S. CHIP INDUSTRY FENDED OFF THE JAPANESE CHALLENGE NOT THANKS TO PROTECTIONISM, BUT INNOVATION

A second example of American success in innovation comes from the EDA tools market. Today's chips have many millions or billions of microscopic transistors, each of which open and close electric currents to produce the 1s and 0s that make computing possible. Chips with so many tiny components can't be designed by hand, nor can each transistor be tested one-by-one. Instead, EDA software tools model how chips will function and automate the layout of transistors and other components of a chip's design. Three U.S.-based companies dominate the EDA market: Cadence, Synopsys, and Mentor, the last of which is owned by Germany's Siemens. This market share gives the United States immense power. Washington's restrictions on Huawei have focused in part on cutting off its chip design arm from EDA tools, which makes it all-but-impossible to design advanced chips. No other country has capabilities comparable to America's in chip design software. This provides a competitive business advantage and a useful geopolitical tool.

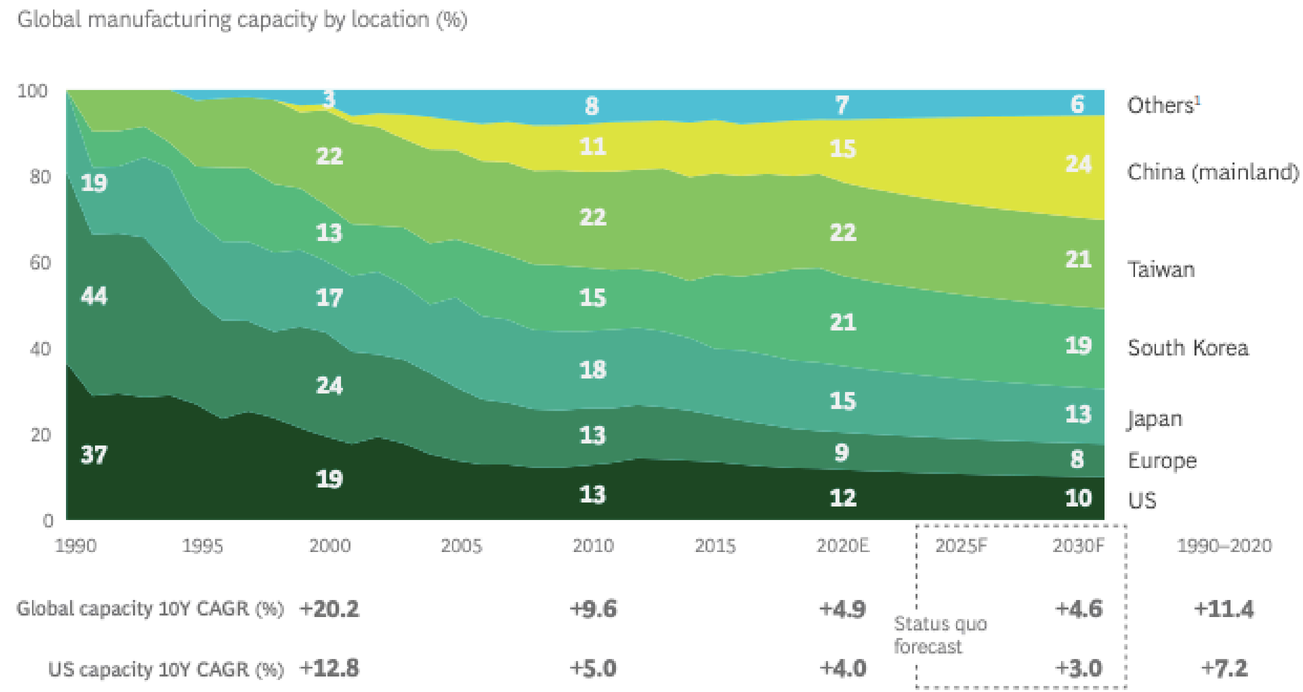
How did the U.S. develop this dominant position in chip design software? In 1982, under the auspices of the Semiconductor Research Corporation (SRC), a research consortium backed by government and industry, centers of excellence in computer-aided design were established at Carnegie Mellon University and University of California, Berkeley. SRC poured money into these two universities, spending $34 million at Carnegie Mellon and $54 million at Berkeley over the subsequent years. The result was a flurry of startups producing design software—something that no other country had. Over two decades, most of these startups consolidated into the three firms that dominate the industry today. If it weren't for the funding of these programs at America's research universities, the United States might not have been able to impose effective export controls on Huawei today.

SUPPORT THE FUTURE, NOT THE PAST

As the U.S. government considers how to support semiconductor firms facing competition from China, it should keep these two historical examples in mind. Many of today's chips will be obsolete in the time it takes Congress to pass legislation affecting them. To succeed, companies not only need advanced technologies, but they also need effective business models—something the government is unlikely to help them with. Given China's willingness to hand out huge sums to its corporations, the United States is unlikely to win a subsidy arms race. Nor should it try. Much like in the case of Japanese competition, the U.S. semiconductor strategies that have worked in the past have supported research into the technologies of the future, then left it to companies to devise profitable business models.

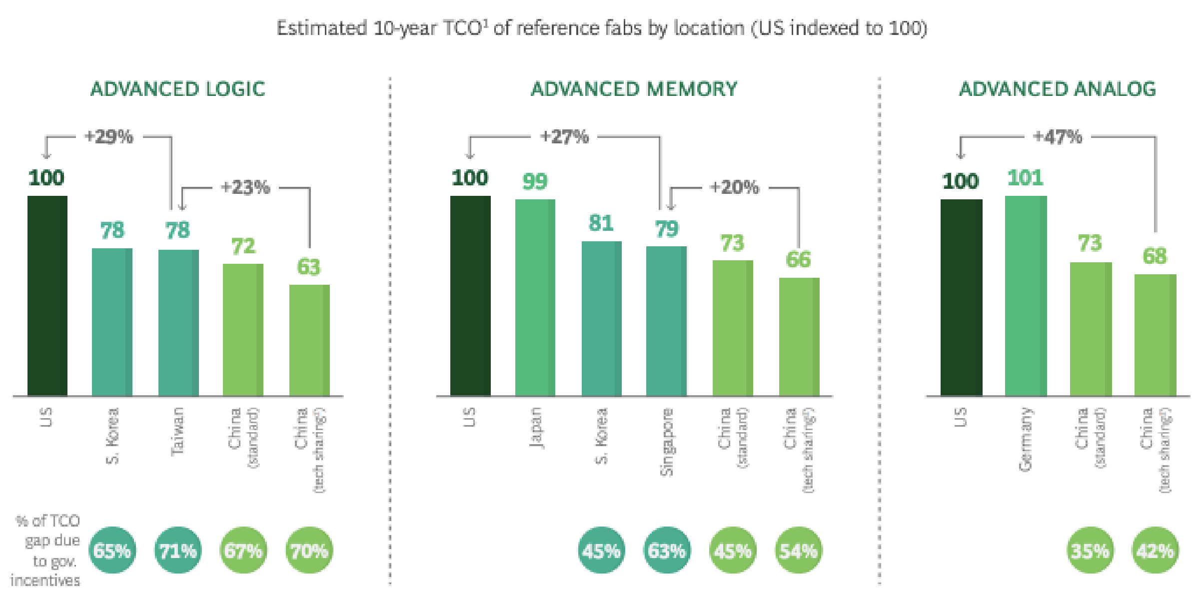
The first step in such a strategy is to consider how the industry looks today, and where the United States faces potential economic and strategic vulnerabilities. The semiconductor industry is commonly broken down into five parts, each of which is needed to produce a chip:

Figure 1: Changes to the Chip Manufacturing Landscape

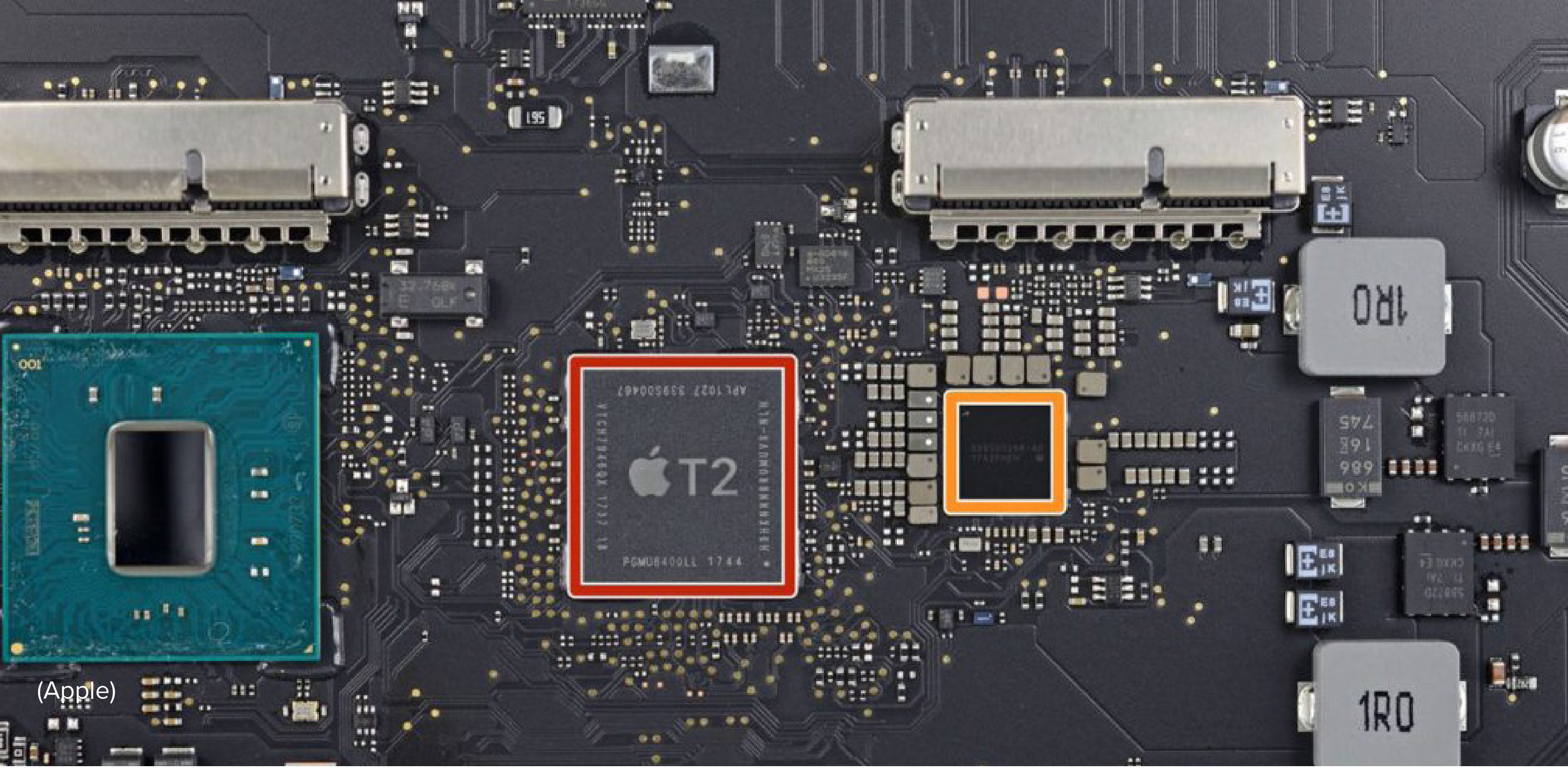


Source: Antonio Varas, Raj Varadarajan, Jimmy Goodrich, Falan Yinug, "Government Incentives and US Competitiveness in Semiconductor Manufacturing," *Semiconductor Industry Association & Boston Consulting Group,* September 2020, https://www.semiconductors.org/wp-content/uploads/2020/09/Government-Incentives-and-US-Competitiveness-in-Semiconductor-Manufacturing-Sep-2020.pdf

Figure 2: Cost Differential of Semiconductor Fabs in the U.S. and Competitors



Source: Antonio Varas, Raj Varadarajan, Jimmy Goodrich, Falan Yinug, "Government Incentives and US Competitiveness in Semiconductor Manufacturing," *Semiconductor Industry Association & Boston Consulting Group,* September 2020, https://www.semiconductors.org/wp-content/uploads/2020/09/Government-Incentives-and-US-Competitiveness-in-Semiconductor-Manufacturing-Sep-2020.pdf



(Apple)

1. Chip Design
2. Electronic Design Automation Software
3. Semiconductor Manufacturing Equipment
4. Manufacturing (aka Fabrication)
5. Testing and Packaging

Of these, the United States is the clear leader in chip design, driven by companies like Qualcomm and AMD in addition to big tech firms like Apple and Google, which in recent years have invested heavily in chip design.[5] EDA software, as mentioned above, is dominated by three U.S.-based firms. Semiconductor manufacturing equipment is produced by a small number of firms, the biggest of which are located in three countries: the United States, Netherlands, and Japan. It is extraordinarily difficult to create an advanced chip without using American manufacturing equipment. When it comes to chip design, design software, and manufacturing equipment, most experts interviewed for this report expect that the United States will retain its market position in the coming years.

In contrast, America's market share has waned in the final two segments of the industry: fabrication and testing and packaging. Testing and packaging has been outsourced to low-cost countries for decades, as it was long seen as low value, though this perspective is beginning to change. More important has been the offshoring of fabrication. As recently as 1990, over a third of semiconductors were manufactured in the United States. Today, only 12% are. The key reason, as Figures 1 and 2 suggest, is cost. A study by the

5 Tripp Mickle, "Apple Is the Newest Chip Giant in Town," *Wall Street Journal,* June 23, 2020, https://www.wsj.com/articles/apple-is-the-newest-chip-giant-in-town-11592910000.

Semiconductor Industry Association and the Boston Consulting Group found that, depending on the type of fab, new facilities are around 20% cheaper in South Korea and Taiwan and 30% cheaper in China.
Is the offshoring of manufacturing a problem for the United States? Some analysts argue that it is not because foreign countries' subsidization of semiconductor manufacturing has increased the profits of U.S.-based design firms. And there is as much money made in chip design as in manufacturing.

However, the offshoring of manufacturing could have three negative consequences for the United States. First, and perhaps most worrisome, is the risk to electronics supply chains in the event of a massive earthquake or a war in Asia. The most advanced manufacturing today takes place at TSMC's facilities in Taiwan, which mostly produce chips for smartphones and computers, but which also manufactures electronics for America's F-35 fighter. Amid tension with China, it is increasingly plausible to imagine scenarios in which American access to Taiwanese manufacturing was severed, imperiling the entire electronics industry. If TSMC's facilities in Taiwan were knocked offline, it could cause years of delays to computer, data center, and smartphone production.

AMERICA'S ABILITY TO CONTROL CHINA'S ACCESS TO TECHNOLOGY—A TOOL THAT WASHINGTON HAS USED REPEATEDLY AGAINST CHINESE TECH FIRMS LIKE HUAWEI IN RECENT YEARS—WILL BE ERODED AS MORE MANUFACTURING HAPPENS OFFSHORE

Second, America's ability to control China's access to technology—a tool that Washington has used repeatedly against Chinese tech firms like Huawei in recent years—will be eroded as more manufacturing happens offshore. American export controls are still effective today, given that even foreign manufacturing facilities all need U.S. equipment to function and are therefore subject to U.S. Commerce Department rules. If more manufacturing moves offshore though, companies may try to replace U.S. technology in their supply chains to avoid U.S. restrictions.
Finally, the shift to offshore production can create a self-reinforcing negative spiral. Offshoring degrades the workforce with the skills needed to invent new

production techniques in the United States. Yet, offshoring matters for manufacturing quality, too. In producing semiconductors, quality is measured by "yield," the share of each silicon wafer that produces functional chips. Many industry experts believe there is an inescapable relationship between volume and yield because the volume of production provides opportunity to learn, eliminate mistakes, and thus improve yield.[6] Some observers argue that this is why Intel, which produces its own chips and which used to have the most advanced manufacturing processes, has fallen behind TSMC, which produces for many companies and thus has far higher production volumes than Intel.[7]

ARE SUBSIDIES THE ANSWER?

These dynamics have led some analysts and officials to call for government support for semiconductor manufacturing. The semiconductor industry is, not surprisingly, in favor.[8] But supporting the chip industry only makes sense if government help produces benefits beyond those that accrue to the companies receiving aid . Some legislation in Congress, however, has proposed broad-based financial support to the construction of fabrication facilities. This is not a recipe for spending money wisely. According to the SIA/BCG study, a new facility for producing logic chips can easily cost $20 billion. A new fab in China, the same study found, is around 30% cheaper. Making up the cost differential completely would require $6 billion in subsidies—all for a single fab. Compare that prodigious sum to the tens of millions of dollars of well-placed research grants that seeded the entire EDA industry and it is far from clear this is the best way to support the chip industry.

Given that U.S. semiconductor export controls are effective because of

6 Interviews with industry experts.

7 Joel Hruska, "Rumor: TSMC Won't Build New Capacity for Intel, Views Orders as Temporary," *Extreme Tech,* July 30, 2020, https://www.extremetech.com/computing/313343-rumor-tsmc-wont-build-new-capacity-for-intel-views-orders-as-temporary.

8 Antonio Varas, Raj Varadarajan, Jimmy Goodrich, Falan Yinug, "Government Incentives and US Competitiveness in Semiconductor Manufacturing," *Semiconductor Industry Association & Boston Consulting Group,* September 2020, https://www.semiconductors.org/wp-content/uploads/2020/09/Government-Incentives-and-US-Competitiveness-in-Semiconductor-Manufacturing-Sep-2020.pdf.

America's monopoly position in the EDA software used to design chips and certain types of equipment used to manufacture them, it would be more useful for America's foreign policy purposes to support these subsectors rather than subsidizing the construction of new fabs. As for the risk that an earthquake or war in Asia disrupts Taiwanese chip production, it would be smarter to mitigate those risks directly—by better defending Taiwan, for example—rather than trying to duplicate TSMC's production facilities.

The bigger problem of subsidizing today's technology is that it will soon be outclassed by something new. Though there are many chips produced using older processes today, the largest share of revenue goes to the newest processes.[9]

Historically, manufacturing processes tend to advance after only two or three years. The cutting edge is always moving forward. This makes government efforts to boost semiconductor manufacturing challenging. Arizona, for example, used a variety of financial incentives to convince TSMC to build a small new local facility. The fab will produce chips at the 5 nanometer node, which is TSMC's most advanced today. But by the time the facility is in operation, TSMC plans to be producing more advanced chips in Taiwan via its 3 nanometer node. So Arizona will be getting second-best technology.

FOCUS ON TOMORROW'S TECHNOLOGIES

Rather than targeting today's cutting edge and being left behind by technological progress, the U.S. government should support the development of processes and materials that are not currently in production and that may be too risky for companies to invest in. This is a sphere where the U.S. government has historically played an important role. The Defense Advanced Research Projects Agency (DARPA) played a major role in funding microelectronics since the industry's earliest days. Some of the first major orders for semiconductors came via the Minuteman II ICBM program and for the Apollo Space Capsule's guidance

9 Anton Shilov, "TSMC Boosts CapEx by $1 Billion, Expects N5 Node to Be Major Success," *AnandTech,* January 22, 2020, https://www.anandtech.com/show/15420/tsmc-boosts-capex-by-1-billion-expects-5n-node-to-be-major-success.

computer. The U.S. government has a strong track record in funding next-generation technologies that companies later commercialize.

FOCUSING ON NEXT-GENERATION TECHNOLOGIES RATHER THAN TODAY'S LEADING EDGE IS PARTICULARLY IMPORTANT BECAUSE IT AVOIDS GETTING TRAPPED BY TODAY'S TECHNOLOGY PARADIGMS.

Focusing on next-generation technologies rather than today's leading edge is particularly important because it avoids getting trapped by today's technology paradigms. The example of Intel in the 1980s—abandoning the cheap DRAM market amid Japanese competition and pioneering chips for PCs, a move that made it more valuable than all Japanese chip producers combined—is instructive. Entrepreneurs are always on the look for disruptive technologies. Rather than simply supporting incumbents—which might be on the edge of being disrupted themselves— the U.S. government should push the cutting edge forward by funding basic research and early stage technologies, and trust Silicon Valley to work out the business model. It has always found a way to do so in the past.

Given today's market structure, it would be very expensive for the United States to move from a 12% to 20% market share in semiconductor fabrication using existing technologies. It would be more strategic to bet on disruptive technologies—exactly the type of technologies that America's research universities already produce, and which U.S. firms have a track record of commercializing. Recent decades have seen plenty of disruption in chip design. Existing U.S. government programs are supporting research into advanced packaging technologies, for example. Given America's reliance on foreign fabs, we should also be funding research into next-generation materials and manufacturing processes that have the potential to disrupt the existing manufacturing paradigm.

Moreover, the process of semiconductor fabrication needs major disruption if it is to continue delivering enhancements in computing power. The International Roadmap for Devices and Systems, the joint industry and academic body that agrees on an annual "roadmap" for the future direction of semiconductor technology, has noted that the process of shrinking transistors is facing new challenges. Very roughly speaking, the number of transistors on a chip is correlated with its computing power. The earliest chips in the 1960s had just a handful of transistors; today, Apple's new M1 chip has 16 billion.[10] Fabrication technologies, which made it possible to shrink transistors, therefore were crucial to technological advance.

Now, however, the process of shrinking transistors "will reach fundamental limits . . . at the end of this decade," the IRDS roadmap predicted in 2020.[11] It is implausible that technological progress will simply stop. The IRDS argues that quantum technologies—which offer the prospect of computers that solve certain problems orders of magnitude more rapidly than today's computers—may at that point begin to be broadly applied, though other experts are skeptical that quantum computing will find commercial application in such a short time horizon. What is clear is that the current model of semiconductor manufacturing not only faces disruption over the next decade—it needs disruption if we are to continue improving computing power. Rather than spending money trying to replicate existing fabs in South Korea and Taiwan, we should be exploring next-generation technologies that would leapfrog them. This isn't just smart technology policy. Its also crucial for computing technology to continue progressing.

Some experts are expecting design, a field where the United States leads, to play a progressively larger role in driving performance improvements as transistor shrinkage slows.[12] The more that design, rather than manufacturing, drives performance, the less strategic manufacturing processes become.

Similarly, the techniques needed to improve manufacturing processes may not necessarily come from the companies that manufacture chips. As previously discussed, fabs in China, Taiwan, and South Korea all heavily rely on equipment produced in the Netherlands, Japan, and the United States. Building on existing U.S. strengths in manufacturing equipment is more likely to yield economic and strategic benefits than trying to subsidize our way to higher market share in fabrication, especially as fabrication itself faces looming technological challenges. Finally, although experts are divided on whether quantum computing techniques will gain practical applicability in the coming decade, if quantum computing becomes commercially viable it would transform the industry. Given existing U.S. strengths in quantum computing research in academia and at corporations like IBM, Microsoft, Intel, and Google, this is an additional area where additional U.S. government investments could have a meaningful impact.

10 "Apple unleashes M1," *Apple*, November 10, 2020, https://www.apple.com/newsroom/2020/11/apple-unleashes-m1.

11 "International Roadmap for Devices and Systems (IRDS) 2020 Edition," Institute of Electrical and Electronics Engineers, 2020, https://irds.ieee.org/editions/2020.

12 Greg Yeric, "IC Design after Moore's Law," *IEEE - Solid-State Circuits Society*, December 18, 2019, https://www.youtube.com/watch?v=q5PcFsG9X24.

SUPPORTING THE SEMIC

2

ONDUCTOR WORKFORCE

The semiconductor industry is a knowledge-intensive field demanding a wide spectrum of deeply specialized experts to design and manufacture chips. Many entry-level jobs at top firms require masters- or doctoral-level training as well as practical industry experience. Workers often hyper-specialize in a particular process or technology, potentially becoming one of just a few dozen such experts worldwide in their field as they develop expertise on the job. From start to finish, it can take a decade or more to train a worker to become productive in the industry.

America's pipeline for chip designers has hollowed out over the last two decades as software has increasingly enticed top technical talent away from semiconductors. Software engineering jobs in the United States typically pay better, can require significantly less training, are at more well-known companies, and offer significantly more flexible career paths. The chip industry has lost its comparative advantage for knowledge workers as the software industry has skyrocketed in size, scale, and wealth.

In numerous interviews with policymakers and industry leaders, we consistently heard about the "high labor costs" of U.S. semiconductor talent and the need to lower these costs to make America more competitive with the labor cost structures in Taiwan, South Korea, and China.

However, that thinking is precisely the opposite of how U.S. policymakers should be approaching the industry's critical workforce challenge. Rather than trying to lower salaries and make the industry even less compelling to potential workers who have abundant choice in their careers, policymakers and industry leaders need to make the industry far more attractive for top technical talent, including matching comparable software salaries, dramatically improving the financial calculus of education and training in semiconductors, and upgrading the flexibility of careers in the industry.

THE EDUCATION OF A SEMICONDUCTOR ENGINEER

Up until the 1970s, the semiconductor and software industries essentially offered identical pipelines for workers[13] (and indeed, at some schools like MIT and University of California, Berkeley, the two fields remain organized within the same department[14]). Students attended universities equipped with early computers, took lectures from faculty pioneering these nascent fields, and graduated into this new industry where it was assumed that they would apprentice for multiple years before being productive employees.[15]

Yet, a slow divergence between these fields that began in the 1980s and 1990s has accelerated in the past two decades, creating vastly different pipelines for workers. First and most importantly, software engineering has become ever more democratized, opening up the field to new workers at all ages. Computers, which were once only available in multi-million dollar computing centers on university campuses, are now widely available to every American.[16] The open-source movement in software has allowed any budding engineer with access to a computer to tinker with existing software and build their own—all for free.[17]

Barriers to software engineering careers have also been eliminated through better and cheaper tooling as well as innovative education programs. Today, many of the most important software development tools are widely available for free.[18] More advanced software frameworks and programming languages as well as cloud computing have lowered the cost and skill required for building useful software.[19] At the same time, education entrepreneurs

13 For an early history of these fields, see: Paul Ceruzzi, *A History of Modern Computing*, 2nd Edition, (MIT Press, 2003). Computer science's intellectual development derived from electrical engineering at institutions like MIT and from mathematics at universities like Stanford.

14 MIT students in electrical engineering and computer science all major in "Course 6."

15 Atsushi Akera, *Calculating a Natural World: Scientists, Engineers, and Computers During the Rise of U.S. Cold War Research,* (MIT Press, 2008). For a perspective on women's changing participation in the field, see: Janet Abbate, *Recoding Gender: Women's Changing Participation in Computing,* (MIT Press, 2017).

16 American Community Survey data from 2018 indicates that 91.8% of households have access to computers (including smartphones) and 85.4% of households have access to the internet. Digest of Education Statistics, National Center for Education Statistics, https://nces.ed.gov/programs/digest/d19/tables/dt19_702.60.asp.

17 For more on open source and its effect on software development, see: Christopher Tozzi, *For Fun and Profit: A History of the Free and Open Source Software Revolution,* (MIT Press, 2017.)

18 A prototypical example is Apple, which makes its Xcode integrated development environment (IDE) free, but charges for publishing an app on its App Store.

19 This has led to the development of the so-called "lean startup," a software company that can be built for very little money using off-the-shelf parts connected together. For more, see the extremely popular: Eric Ries, *The Lean Startup: How Today's Entrepreneurs Use Continuous Innovation to Create Radically Successful Businesses,* (Crown Business, 2011).

have launched dozens of in-person and online software "boot camps," which can turn a novice coder into a competent, employable one in a matter of months.[20] Some of these programs, like Lambda School, don't even require upfront tuition fees, but rather will take a percentage of their students' future earnings through an instrument known as an "income share agreement,"[21] lowering the immediate financial burden for education in this sector.

During the same time though, chip engineering has moved in the opposite direction. As chip nodes have shrunk ever closer to the limits of physics, the skill and cost of equipment required to do pathbreaking work in the field has gone up exponentially. Whereas in the 1960s and 1970s, a student could tinker with state-of-the-art computers in college research laboratories, today, extreme ultraviolet lithography equipment from suppliers like ASML can run more than $120 million per machine, putting this technology out of range of even the most well-endowed university.[22]

While RISC-V and OpenRAN are increasingly popular open-source ecosystems in hardware, the reality is that the vast majority of chip design tools like electronic design automation packages (EDA) are closed-source and extraordinarily expensive (although EDA companies often provide cheaper educational licenses to students while in school).[23] Licenses for mid-range software to be productive in the field can easily total tens of thousands of dollars per year per user, with pricing that is completely opaque. In fact, concerns about pricing are so high that DARPA initiated a $1.5 billion program in 2017, called the Electronics Resurgence Initiative, designed to incubate cheaper and more competitive chip design software.[24] In short, there remains no easy way for aspiring chip designers to get in the field without deep and upfront resources at their disposal.

Unsurprisingly, as the barriers to learning computer science (CS) have fallen, enrollments have soared. College Board, which administers the Advanced Placement high school curriculum, has

20 See, lists of software bootcamps, such as Course Report's "The 54 Best Coding Bootcamps," https://www.coursereport.com/best-coding-bootcamps.

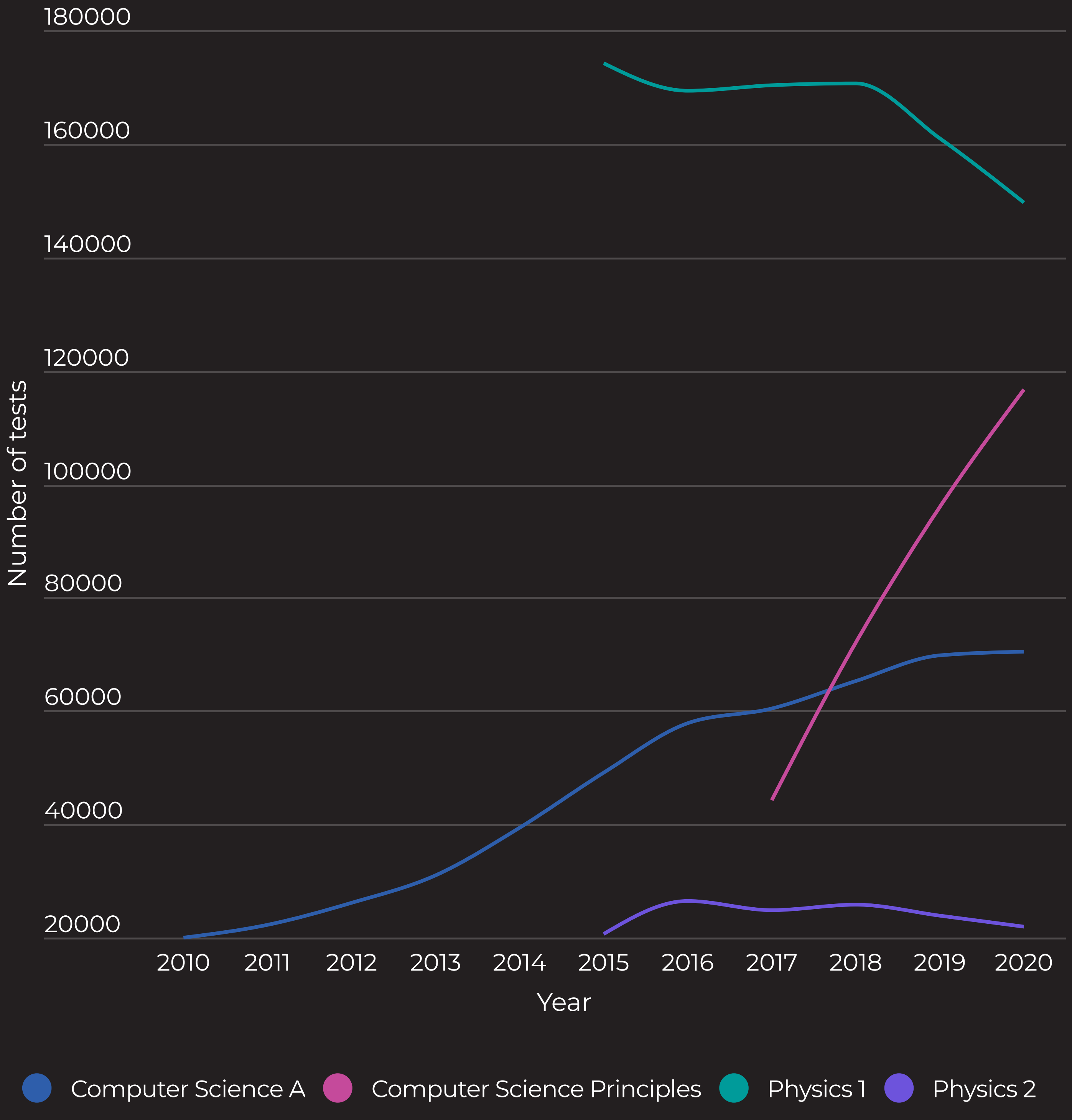
21 Eric Peckham, "How income share agreements will spark the rise of career accelerators," *TechCrunch*, December 31, 2019, https://techcrunch.com/2019/12/31/how-income-share-agreements-will-spark-the-rise-of-career-accelerators/.

22 For more on ASML's technology, see: Carrick Flynn, "The chip-making machine at the center of Chinese dual-use concerns," Brookings Institution, June 30, 2020, https://www.brookings.edu/techstream/the-chip-making-machine-at-the-center-of-chinese-dual-use-concerns/.

23 This cost leads to ongoing discussions about how to hack around these high costs to entry. See, for example: David Schneider, "How to Design a New Chip on a Budget," *IEEE Spectrum*, February 5, 2018, https://spectrum.ieee.org/tech-talk/computing/hardware/lowbudget-chip-design-how-hard-is-it.

24 "DARPA Electronics Resurgence Initiative," Defense Advanced Research Projects Agency,. https://www.darpa.mil/work-with-us/electronics-resurgence-initiative. See, also: Kevin Fogarty, "Will Open-Source EDA Work?" *SemiconductorEngineering*, June 26, 2019, https://semiengineering.com/will-open-source-eda-work/.

Figure 3: AP Tests by Subject



Source: Data from "AP Exam Volume Changes (2010-2020)," College Board, https://research.collegeboard.org/programs/ap/data/participation/ap-2020.

seen students sitting for its Computer Science A exam soar from about 20,000 in 2010 to more than 70,000 in 2020—the largest growth among the College Board's more than three dozen subjects during this decade.[25] The organization also introduced a Computer Science Principles course in 2017, which debuted with 44,000 high school exam takers and grew to almost 117,000 in 2020 (see Figure 3 and 4). That growth in popularity for CS is not mirrored in other sciences relevant to hardware engineering. The College Board's data shows calculus exam takers are nearly flat over the decade, barely up in chemistry, and declining in physics.

On the other side of the education pipeline, the National Science Foundation's Survey of Earned Doctorates shows that CS has grown from about 600 doctorates in 1989 to 2,228 in 2019 (growth of 370%), while electrical engineering has gone from about 1,000 doctorates to about 1,800 in the same period (growth of 80%).[26] While electrical engineering doctorates are not the only field of study applicable to the chip industry (chemistry, materials science, and physics graduates are also courted by companies depending on their exact subfields), the pipeline for chip workers has not kept pace with the rapid growth in computer science.

In short, software engineering has lowered barriers and costs while making developer tools more accessible to aspiring workers. Chip engineering has gone in the opposite direction, making it more expensive and harder than ever to join the field. It's little wonder then that the software talent pipeline is flush, while chip firms struggle to attract workers in the United States.

CHIP CAREERS TODAY ARE MORE WORK WITH LESS PAYOFF

The democratization of software engineering is coupled with powerful inducements to learn to code: widely available high salaries, career flexibility, and market-competitive stability compared to chip engineering careers.

Aggregate labor data can hide many of these software career advantages. For instance, the Bureau of Labor Statistics (BLS) reports that salaries are roughly equal between software developers and computer engineers across all percentiles, with computer hardware engineers earning about 6-12% more than software engineers on average.[27] Data from visa

25 Data from "AP Exam Volume Changes (2010-2020)," College Board,https://research.collegeboard.org/programs/ap/data/participation/ap-2020.

26 Data from "Doctorate Recipients from U.S. Universities: 2019 Data Tables," National Science Foundation, December 1, 2020, https://www.nsf.gov/statistics/srvydoctorates/.

27 Data from "Occupational Employment Statistics," Bureau of Labor Statistics, May 2019, https://www.bls.gov/oes/current/oes_stru.htm. Category codes used for software are 15-1256, 15-1255, and 15-1251, while for computer hardware engineers it is 17-2061.

applicants supplied by the Department of Labor shows a greater variance, with semiconductor jobs having a 30-50% wage premium over software engineering jobs across salary percentiles.[28]

Yet, according to the same BLS data, there were roughly 68,000 computer hardware engineers in the United States, compared to more than 1.4 million software engineers (and even more if adjacent labor categories are included). In the visa dataset analyzed for this report, there were 14,375 semiconductor visa applications in fiscal year 2020, compared to 228,411 software visa applications. Perhaps more directly, if we look at applications with wage rates above $100,000, there were 10,557 applications in semiconductors compared to 77,071 applications in software.

The key point here is labor market depth: The software industry has many more jobs—including high-paying jobs—than the semiconductor labor market. That market depth gives individual engineers more flexibility and stability in software since there are more available positions.

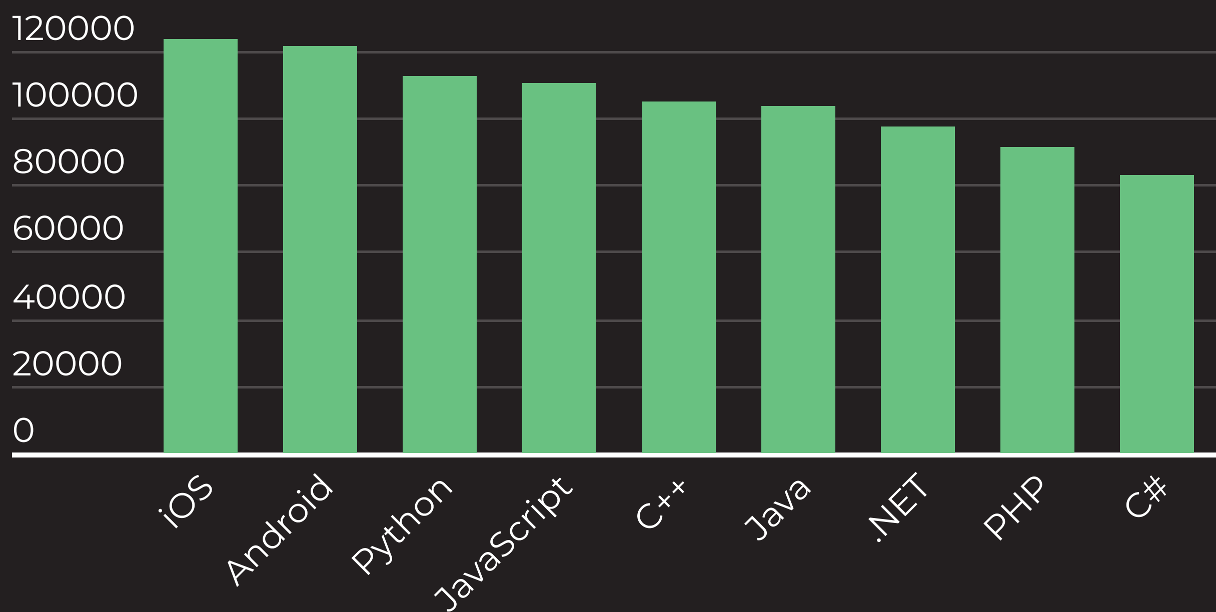
Perhaps even more importantly, software engineers can find jobs at a vast range of potential companies. There are hundreds of publicly traded American software companies hiring software engineers, not to mention governments, research labs, nonprofits, and more. Since software can be developed remotely, many of these jobs are available to any American with an internet connection and a computer. On the hardware side, however, there are just a few dozen companies that demand the unique skillsets of chip designers and manufacturers, with most companies requiring workers to be present in offices or fabs.

Considering the lengthy training timeline for chip engineers, the small labor market and relatively limited wage premium in semiconductors makes the individual financial calculus of these careers very tough. Worse for the industry, the depth of the software labor market always beckons to hardware engineers, who can make the leap to software with reasonable effort. Online forums for industry professionals like Reddit, HackerNews, Quora, Blind and others are filled with requests for advice on making this transition.

When it comes to industrial power, software is America's greatest industry. Six of the top ten largest companies in the world by market cap are American software companies (with Apple being an unusual hybrid company between software and

28 Data from "Performance Data: LCA Programs (H-1B, H-1B1, E-3)," Office of Foreign Labor Certification, Department of Labor, https://www.dol.gov/agencies/eta/foreign-labor/performance. Data was for Fiscal Year 2020. NAICS codes for semiconductors included 334111, 3344, 33441, 334412, 334413, 334416, 334417, 334418, 334419, and 333242, while for software, they included 541511, 511210, and 541512. 14,375 semiconductor job records were included, and 228,411 software records were included.

Figure 4: Average Software Engineer Salary by Language in USA (2021)



Source: "What is the Average Software Developer Strategy Around the World," DAXX, February 17, 2021, https://www.daxx.com/blog/development-trends/it-salaries-software-developer-trends

hardware).[29] The other companies in the top ten are the two Chinese software giants Alibaba and Tencent, Saudi Aramco, and Warren Buffet's holding company Berkshire Hathaway. The extreme success of software companies in the United States allows them to pay significantly higher wages, offer a better working environment, and compete for the best talent unencumbered by most notions of cost structure.

Taiwan and South Korea lack the same success in software, with neither having a world-class software company that is internationally competitive. For domestic workers in these two economies, the semiconductor industry is one of the most lucrative opportunities available. In November 2020, TSMC announced that it would raise wages by 20%, but would

29 The companies are Apple, Microsoft, Amazon, Alphabet, Facebook, and Visa. See "Global Top 100 companies by market capitalisation," PwC (PricewaterhouseCoopers), July 2020. https://www.pwc.com/gx/en/audit-services/publications/assets/global-top-100-companies-june-2020-update.pdf

also offset bonuses to compensate.[30] According to the chip fab, the average worker makes roughly $56,000. That wage is significantly below comparable American salaries, but is nearly 2.5 times the rate of the average Taiwanese full-time worker.[31] In short, local conditions make chip jobs—and the long education and training courses required to attain them—very attractive for workers eager for financial success and a stable future.

Figure 5 Average Software Engineer Salary by Language in USA

China, which also has a comparatively low per capita gross domestic product (GDP), has understood this comparative dynamic and has embarked on attracting workers to this critical technology industry with globally competitive pay packages—as opposed to *locally* competitive ones. The country and its leading chip companies have made salary offers in the millions of dollars for star chip designers, and they will pay other workers who relocate to China or work abroad for Chinese companies hundreds of thousands of dollars a year in salary, most notably through the Thousand Talents Program.[32]

OPENING THE PIPELINE AND FLUSHING IT WITH CASH

Too much of American policymaking focuses on "lowering costs" instead of making an industry relatively more attractive to workers. The United States has an open and competitive labor economy, and workers are encouraged and incentivized to choose the career paths that give them the highest wages and the most job satisfaction. The technically talented workers that chip companies need are adaptable and have many other directions they can take their careers to maximize their expected incomes and quality of life.

The United States needs to give its domestic chip industry a comparative advantage in the labor market, particularly from the siren song of U.S. software giants.

First and foremost, the United States must aggressively and rapidly open up and democratize computer hardware engineering through open-source and experimental manufacturing programs. A key goal should be to make the mainstream tools of the field free and

30 Lisa Wang, "TSMC reveals wage hike plan," *Taipei Times*, November 14, 2020, https://www.taipeitimes.com/News/biz/archives/2020/11/14/2003746864.

31 Data from Directorate-General of Budget, Accounting and Statistics, Executive Yuan, Republic of China, https://eng.dgbas.gov.tw/ct.asp?xItem=46518&ctNode=3339. Average annual salary in U.S. dollars as of September 2020 for full-time workers was $22,789.

32 See, for example: Yimou Lee, "China lures chip talent from Taiwan with fat salaries, perks," *Reuters*, September 4, 2018, https://www.reuters.com/article/us-china-semiconductors-taiwan-insight/china-lures-chip-talent-from-taiwan-with-fat-salaries-perks-idUSKCN1LK0H1.

openly accessible to students, hobbyists, and new entrants into the labor force.

THE UNITED STATES NEEDS TO GIVE ITS DOMESTIC CHIP INDUSTRY A COMPARATIVE ADVANTAGE IN THE LABOR MARKET, PARTICULARLY FROM THE SIREN SONG OF U.S. SOFTWARE GIANTS.

Much as open-source has democratized software engineering and ultimately created some of the most valuable companies in the world, forcing open the hardware engineering economy will create significant positive externalities, while still ensuring that companies can develop and protect proprietary and valuable intellectual property.

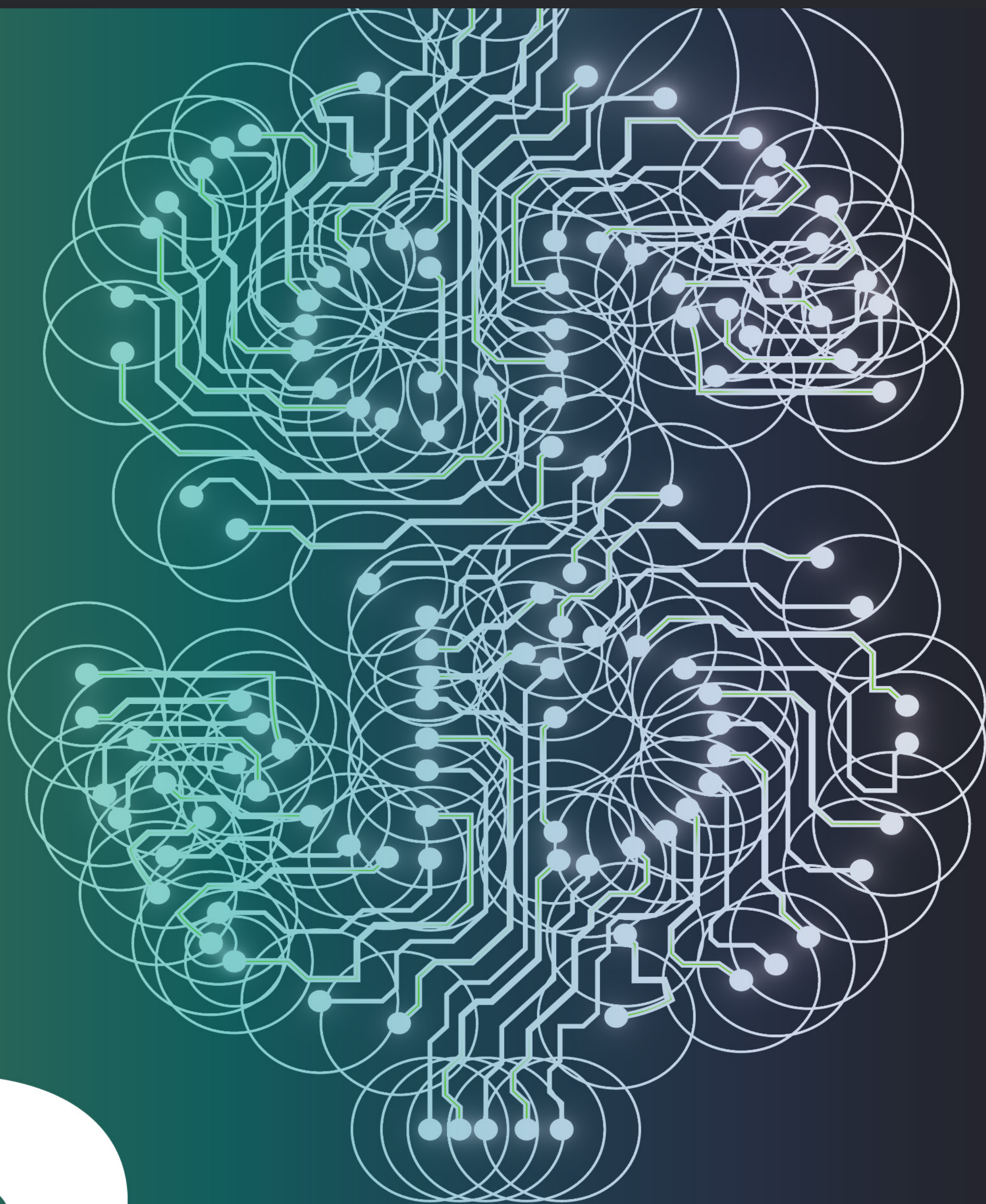
Second, the United States must incentivize more technical talent to build careers in semiconductors by making the career more financially enticing. Options might include additional scholarship dollars and stipends for students in relevant fields while still in college, better funding for experimental projects, more robust stipends for graduate students, and tax credits or other forms of corporate incentives to significantly raise salaries in the industry to give them a more competitive wage premium compared to software careers.

Third, the United States needs to ensure that star chip design talent stays in the United States. Additional flagship grant programs for researchers, incentive funding for venture capitalists to invest in chip startups, and high-priority visa and grant processing can ensure this talent remains in the United States and continues to be attracted from abroad.

Compared to the past, a career in chip design isn't as attractive for American workers today. Policymakers face a choice of either letting the industry wither given the globally competitive labor market, or bolstering the workforce so that an ecosystem of chip firms can flourish. Other countries can be counted on to continue cultivating their own comparative advantages. If the United States can't find a way to attract more skilled workers into semiconductors, then America will find itself increasingly dependent on imports for this critical technology.

3

THE PROMISE AND PARANOIA



OF RISC-V

Today, the cost to design a 7nm chip is somewhere around $100m and 1,000 years of employee labor, far outside the budgets of all but the biggest firms.[33] Proponents of the RISC-V instruction set architecture (ISA) believe it could bring the cost down to $10 million while creating an open-source standardized ecosystem for all computing devices, leveling the global playing field for chip design, and making extensible, modular hardware design available to all universities and companies. RISC-V's rise will spark faster innovation from more designers as the development of shared core designs reduces time to market and increases transparency and security.[34]

Some in government and industry worry that an open-source hardware revolution would undercut America's preeminent position in the chip industry and cede ground to China. However, former Intel CEO Andy Grove once famously quipped that in semiconductors "only the paranoid survive." This paranoia needs to be channeled to ride—not resist—the flow of technological change. The U.S. government must realize that open-source hardware is coming, and it must invest in the future at home to ensure that it is positioned to lead the field.

WHAT IS RISC-V?

An ISA is an abstract model of a computer serving as the boundary between software and hardware, and it is the part of the processor visible to a software engineer.[35] Currently, Intel's x86 ISA dominates the desktop, laptop, and server market, while ARM drives chips inside most smartphones. RISC-V, first conceptualized in University of California,

33 "Keynote: RISC-V in China - Dr. Guangnan Ni, Academician of the Chinese Academy of Engineering," RISC-V International, September 3, 2020, Published: September 8, 2020, https://www.youtube.com/watch?v=k88wnIY7qhc.

34 Krste Asanovic and David A. Patterson, "Instruction Sets Should Be Free: The Case For RISC-V," Electrical Engineering and Computer Sciences University of California at Berkeley, August 6, 2014, https://people.eecs.berkeley.edu/~krste/papers/EECS-2014-146.pdf.

35 "Instruction Set Architecture (ISA)," Kent State University, http://www.cs.kent.edu/~durand/CS0/Notes/Chapter05/isa.html.

Berkeley labs in the 1980s, was realized as an architecture, again at Berkeley, in 2010.[36]

The RISC-V Foundation, established in 2015, aims "to build an open, collaborative community of software and hardware innovators based on the RISC-V ISA." Its members include over a hundred of the world's leading firms in the semiconductor space, including Qualcomm, Huawei, Nvidia, Alibaba, Google, Western Digital, Cadence, and Samsung. Notable exceptions include Arm and Intel, which see RISC-V as a competitor. Of the eleven premier members whose $100,000-250,000 annual membership fee buys a seat on the Technical Steering Committee, eight are headquartered in China.[37]

Alongside its open-source nature, RISC-V features several revisions to the base ISA model, which give it an edge relative to ARM and x86 for certain types of compute. By building around modern innovations in processor design like instruction compression and macro-ops fusion, RISC-V programs can be more efficient compared to other architectures by conducting fewer operations while using the same amount of memory.[38] In RISC-V, instructions that outlive their usefulness can be easily discarded, allowing designers to save precious silicon and letting the ISA easily adapt to future innovations in micro-architecture.[39] Its simplicity and lack of licensing requirements have also made it attractive as a teaching and university research tool, particularly in Europe, opening up the pipeline for chip talent.[40]

While RISC-V is the first open-source ISA to gain momentum, open-source software has already made an enormous impact on the world. Open-source software is code "designed to be publicly accessible—anyone can see, modify, and distribute the code as they see fit. Open-source software is developed in a decentralized and collaborative way, relying on peer review and community production."[41]

RISC-V hopes to emulate a growth

36 Rupert Goodwins, "Chips that pass in the night: How risky is RISC-V to Arm, Intel and the others? Very," *The Register,* March 9, 2020, https://www.theregister.com/2020/03/09/risc_v_intel_amd_arm/.

37 "RISC-V International Members," RISC-V, 2020, https://riscv.org/members/.

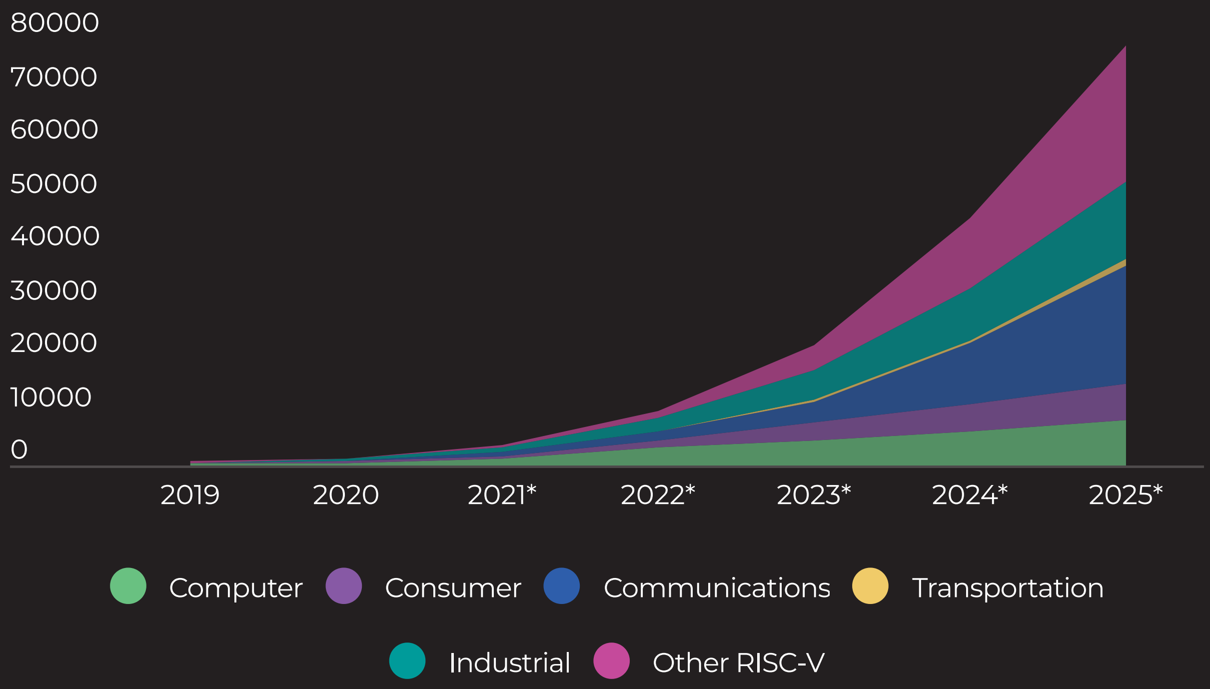
38 Erik Engheim, "The Genius of RISC-V Microprocessors," *Medium*, December 14, 2020, https://erik-engheim.medium.com/the-genius-of-risc-v-microprocessors-b19d735abaa6; and Christopher Celio, Palmer Dabbelt, David Patterson, and Krste Asanovic, "The Renewed Case for the Reduced Instruction Set Computer: Avoiding ISA Bloat with Macro-Op Fusion for RISC-V," Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, July 8, 2016, https://arxiv.org/pdf/1607.02318.pdf.

39 Erik Engheim, "What Is Innovative About RISC-V?," *Medium*, December 24, 2020, https://medium.com/swlh/what-is-innovative-about-risc-v-a821036a1568.

40 Jim Turley, "Why Universities Want RISC-V: Sometimes It's Not About The Technology or The Performance," *Electronic Engineering Journal,* October 27, 2020, https://www.eejournal.com/article/why-universities-want-risc-v/.

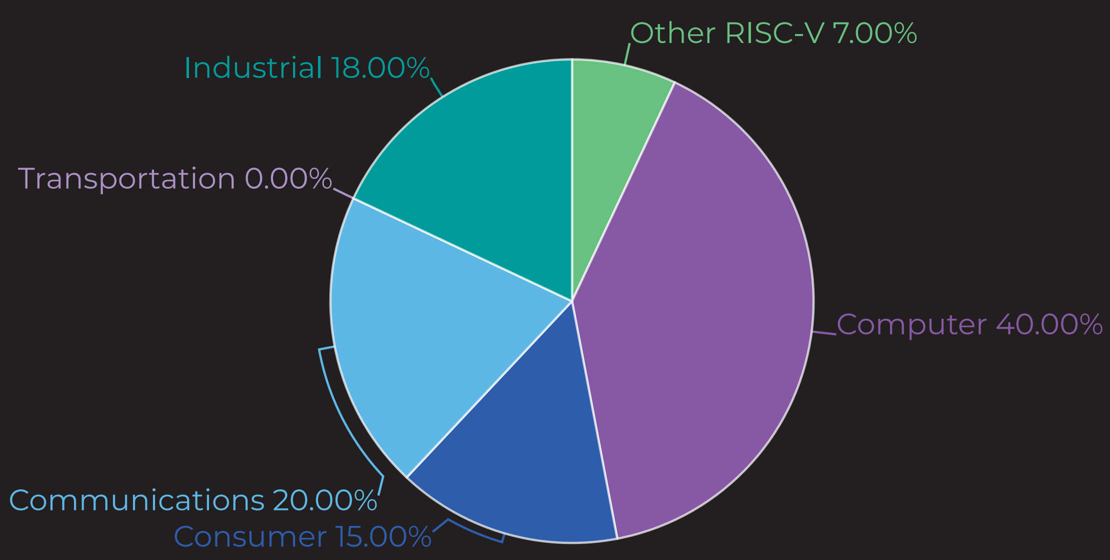
41 "What is open source?" RedHat Inc., 2020, https://www.redhat.com/en/topics/open-source/what-is-open-source.

Figure 5: Total Projected Market Consumption of RISC-V CPU Cores

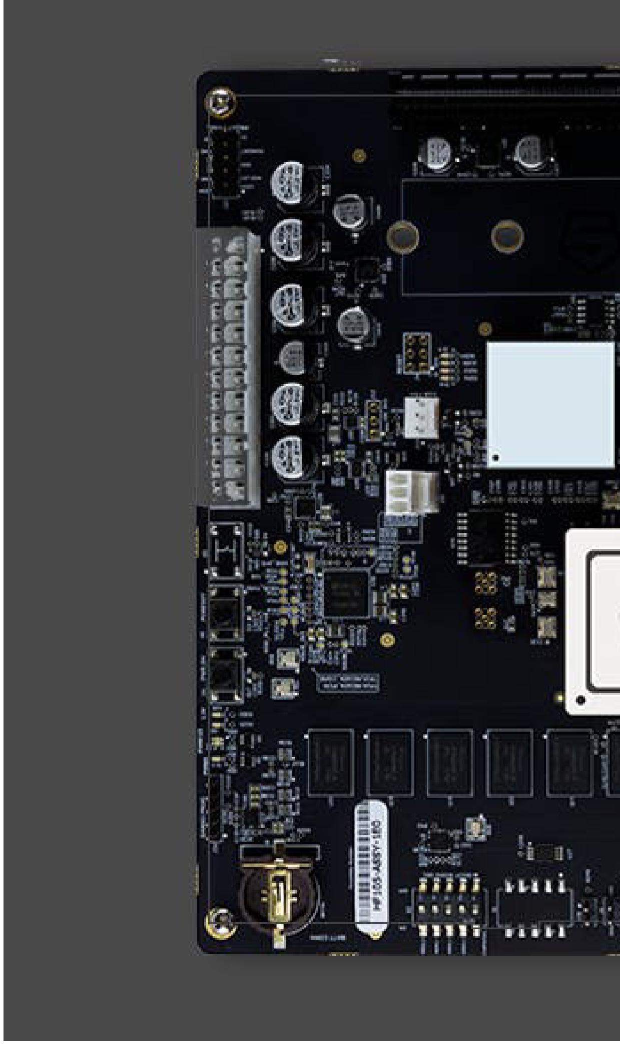


Source: Semico Research Corp

Figure 6: Market Consumption Breakdown of RISC-V CPU Cores in 2020



Source: Semico Research Corp



trajectory akin to network protocol TCP/IP or Linux.[42] Linux, an open-source operating system, was created in 1991 by then 21-year-old Finnish student Linus Torvalds. It started out as a playground for hobbyists and idealists, but eventually became mainstream as thousands of developers' free contributions made it competitive with Microsoft Windows. IBM's announcement in 2000 that it would be investing $1 billion into Linux helped legitimize it in the corporate world, helping to put it on a trajectory where today it remains a major alternative to Microsoft Windows. In servers, it holds a respectable 14% market share.[43]

GROWTH CHALLENGES

RISC-V still has a long way to go to be considered a real competitor to ARM or x86. Open-source hardware faces a far more challenging path to developing its ecosystem than software. First, the technical bar to contribute to an open-source hardware project is much higher and more specialized than most software projects. There are far more people who have picked up a software programming language like C than know enough electrical engineering to make sense of an ISA. Although RISC-V is more straightforward than x86, it still must reconcile the technical input of hundreds if not thousands of contributors, though the centralized RISC-V Technical Steering Committee could accelerate the process more than the decentralized way Linux dealt with problems.

Most importantly, an open-source ISA will struggle to progress without having the actual hardware on hand and creating

42 Krste Asanovic and David A. Patterson, "Instruction Sets Should Be Free: The Case For RISC-V," Electrical Engineering and Computer Sciences University of California at Berkeley, August 6, 2014, https://people.eecs.berkeley.edu/~krste/papers/EECS-2014-146.pdf. The RISC-V Foundation's stated goal is "world domination." "John Hennessy and David Patterson Deliver Turing Lecture at ISCA 2018," Association for Computing Machinery, 2017, https://www.acm.org/hennessy-patterson-turing-lecture.

43 Glyn Moody, "Free software survives downturn," *The Guardian,* January 9, 2002, https://www.theguardian.com/technology/2002/jan/10/internet.onlinesupplement; and Paul Venezia, "Linux at 25: How Linux changed the world," *InfoWorld,* August 24, 2016, https://www.infoworld.com/article/3109204/linux-at-25-how-linux-changed-the-world.html.

robust verification systems.[44] Even if RISC-V gets a critical mass of people in academia and industry developing the theoretical ISA itself, the movement will still need to manufacture on silicon to test alterations to the architecture. Arm and Intel have invested enormous sums into verification for their client companies, and firms that branch out into an immature extensible architecture like RISC-V have their work cut out for them. As verification commonly takes two-thirds of the total effort involved in making a modern System-on-a-Chip (SoC), forcing firms who adopt RISC-V to do this themselves is a major burden.[45] One American startup founded by a group of RISC-V leaders, SiFive, is creating one of the first production-ready chips in this ecosystem, attempting to force a complete production pipeline into existence. However, this process will take years to mature.

Other efforts that will fill out the broader RISC-V ecosystem will take as long or longer. Arm was introduced in 1985 as a challenger to the then-dominant x86. It took 25 years to develop a strong enough ecosystem to enable it to win substantial market share, and only then because Arm became the standard for smartphones and other mobile devices, which grew rapidly in popularity in the late 2000s. The transition to RISC-V should be somewhat more straightforward, however, as Arm and RISC-V are both from the same family of architectures known as reduced instruction set computing.

Entire generations of engineers have cut their teeth on Arm and x86. Even though RISC-V is simpler to work with, most chip designers are specialized to work with x86 and ARM. It will take years to build a new pipeline of professionals, mostly likely those who worked with RISC-V at university, to acquire expertise needed to realize RISC-V's promise. Furthermore, open-source chip design (EDA) tools to

44 Interview with Sultan Mehji, Dec 16, 2020.

45 Ann Steffora Mutschler, "RISC-V Verification Challenges Spread," *Semiconductor Engineering,* December 22, 2020, https://semiengineering.com/risc-v-verification-challenges-spread/.

Xiaomi's newest Mi Smart Band 5 is powered by a Huami RISC-V core

Source: Xiaomi global home page, https://www.mi.com/global/mi-smart-band-5/, accessed February 13, 2021.

compete with incumbents like Synopsis and Cadence are potentially decades away. Without open-source EDA, RISC-V wouldn't be all that different from its competitors—just an open-source instruction set relying on the same expensive, closed-source design tools used by x86 and ARM designers.

VERTICAL-SPECIFIC PROGRESS

Despite these many barriers, RISC-V hopes to ride shifting industry trends to greater market share. In earlier generations, steady improvements in general purpose computing drove chip sales. Now, with Moore's Law slowing down and as more computing is happening in the edge (i.e., in your smartphone, car, or doorbell), instead of in a data center, new requirements that demand optimized domain-specific workloads for a large variety of platforms suit a more flexible architecture like RISC-V.

Internet of Things (IoT) chips comprise the most promising market for RISC-V. Each IoT device, whether a wearable device, an internet-enabled thermostat, or a smart speaker, needs a chip customized for its specific requirements. IoT applications don't necessarily need to be programmable and interface with other applications, making the immaturity of RISC-V compatible software less of a drawback.[46]

46 Interview with Doug O'Laughlin. "But later, people will be able to pull stuff off the shelf and make their own things. It will be the one over time, if the ecosystem builds it, they'll have the most off the shelf cores to make stuff built to order."

Startups in this fragmented space are cost-conscious and have younger, more affordable engineers. As Codasip's Chris Jones argues,

> *With so many new IoT applications emerging, the demand for custom silicon keeps rising. It cannot be reasonably expected for the same semiconductor device to run a wireless protocol in one product, to encode video data in a second consumer device, and to perform facial recognition in a third. A chip could be designed in a general-purpose fashion to handle each of these tasks, however it would then be large and power inefficient. That is why the scalability of RISC-V is so attractive, allowing for different performance/power profiles while preserving the software investment across multiple devices.*[47]

The largest commitment to RISC-V thus far has come from solid-state drive manufacturers, a relatively straightforward application of the ISA. Western Digital has committed to transitioning a billion cores (today's processors are often built with multiple processing cores) to RISC-V, and competitor Seagate in late 2020 rolled out two RISC-V processors.[48] Both firms stand to save considerable sums transitioning away from ARM and thereby avoiding that company's licensing fees. Moreover, they believe their commitments to RISC-V will lead to "lower latency, power savings, higher drive capacities at a faster pace, computational capabilities in storage drives, and improved security for data created at the edge of the network."[49] Other promising markets include vision systems for cars and security cameras, factory-floor applications, and smart agriculture such as tracking livestock.[50]

Semico, in a market research project produced in collaboration with the RISC-V Foundation, estimated in late 2019 that RISC-V would capture 4.5% of overall cores consumed by industry by 2025.[51] Given their rather conservative methodology, which linearly extrapolates from present day survey data, it may underestimate RISC-V's growth.

47 Mark Sinclair, "Celebrating IoTDay: How RISC-V Enables IoT Innovation," RISC-V, April 9, 2019, https://riscv.org/news/2019/04/celebrating-iotday-how-risc-v-enables-iot-innovation/.

48 Carol Sliwa, "Seagate, Western Digital outline progress on RISC-V designs," *TechTarget,* December 10, 2020, https://searchstorage.techtarget.com/news/252493477/Seagate-Western-Digital-outline-progress-on-RISC-V-designs.

49 Sliwa, "Seagate, Western Digital outline progress on RISC-V designs," *TechTarget*.

50 Stephanie Condon, "Fitbits for cows? Building IoT for the industry technology left behind," *ZDNet,* April 16, 2019, https://www.zdnet.com/article/building-iot-for-the-industry-technology-left-behind/.

51 "RISC-V: The New Kid on the Block - 2019 RISC-V CON Silicon Valley," Semico Research Corp., October 2019, Published: October 29, 2019, https://www.youtube.com/watch?v=2nidPbnMBtM.

CHINA RISING

Today, China has the liveliest RISC-V ecosystem. Every major Chinese tech firm seems to boast a RISC-V strategy, with Alibaba producing what may be the world's fastest RISC-V chip targeting artificial intelligence applications. Alibaba also announced its desire to put RISC-V at the center of its future cloud and edge computing strategy,[52] while Xiaomi is selling a wearable with a RISC-V based processor.[53] Huawei has announced it was considering adopting RISC-V as a replacement to ARM for its mobile chips.[54] In all, over 300 established firms and startups are working on RISC-V in China.[55] Chinese firms have popped up at all points in the RISC-V supply chain, from core IP design firms like Alibaba's Dharma Institute and Saifang Technology, to design companies like Zhaoyi Innovation and Beijing Junzheng, and lastly to brand manufacturers like Xiaomi and Huawei.[56]

Why the intense interest? As one Chinese media article explaining the importance of RISC-V begins, "You cannot build a house on someone else's foundation."[57] While PRC leaders dating back to Mao Zedong have prioritized technological independence, the recent U.S. export control restrictions targeting firms like Huawei have led China to redouble efforts to create a self-reliant technological ecosystem.[58] In particular, U.S. sanctions on ZTE, which nearly killed a $10 billion household name firm, led to a "Sputnik Moment" for both

52 Jeffrey Burt, "Alibaba on the Bleeding Edge of RISC-V with XT910," *The Next Platform,* August 21, 2020, https://www.nextplatform.com/2020/08/21/alibaba-on-the-bleeding-edge-of-risc-v-with-xt910/.

53 "Xiaomi Mi Band 4 will work on the new proprietary processor Huangshan No.1," *Geek Tech Online,* https://geektech.me/xiaomi-mi-band-4-will-work-on-the-new-proprietary-processor-huangshan-no-1/.

54 *Huawei Determined to Create a New Ecosystem, RISC-V or a "Replacement" ARM* "华为攻坚方向在生态，RISC–V或"替补"ARM," *EEPW,* May 29, 2019,
https://web.archive.org/web/20190609235628/http://www.eepw.com.cn/article/201905/401037.htm

55 *Big Change in the Chip Industry! Nvidia 'Encircles' Intel, Huawei Unjustly Blamed* "芯片业大变局！英伟达"包抄"英特尔，华为躺枪," *tech.sina.com,* August 18, 2020, https://web.archive.org/web/20200819020952/https://tech.sina.com.cn/csj/2020-08-18/doc-iivhuipn9370616.shtml

56 *Can the Open Source RISC-V be the Antidote to China's "Chip Deficit"?* Recode, 开源的RISC–V能否成为中国"缺芯"的解药？Pingwest, January 18, 2021. https://web.archive.org/web/20210212204023/https://mp.weixin.qq.com/s/ETy5DhytT0W53ZS36EM8YA

57 Gao Xiaoping. "China Chip" Accelerates with New Architectures"郜小平, 南方日报. "国产芯"加速崛起 新架构谁. Nanfang Daily. August 21, 2020. https://web.archive.org/web/20200822185404/https://tech.sina.com.cn/it/2020-08-21/doc-iivhuipn9812460.shtml

58 Julian Gewirtz, "The Futurists of Beijing: Alvin Toffler, Zhao Ziyang, and China's 'New Technological Revolution,'" 1979-1991," *Journal of Asian Studies*, vol. 78, no. 1, 2019, https://www.cambridge.org/core/journals/journal-of-asian-studies/article/futurists-of-beijing-alvin-toffler-zhao-ziyang-and-chinas-new-technological-revolution-19791991/9C3A0A2BA1E1FEE714548E47FA351758.
Ni Guangnan, a professor at the Chinese Academy of Engineering, former chief engineer at Lenovo, inventor of the Han Card that allowed Lenovo computers to process Chinese characters, and at 81 one of the most prominent microchip elder statesmen in the PRC, also had high hopes for this when looking forward to the prospects of open source chips: "RISC-V is likely to develop into one of the world's mainstream CPUs, forming a three-part pattern of Intel x86, Arm, and RISC-V in the CPU field." Liang Ning. *'An Old Tale Of China's Domestic Chip Industry and Operating Systems'* "一段关于国产芯片和操作系统的往事," *Huxiu.com,* April 22, 2018, https://web.archive.org/web/20180422122042/https://www.huxiu.com/article/241195.htmlformer chief engineer of Lenovo. See also: https://web.archive.org/web/20210224032400/https://www.zhihu.com/question/49688274.

industry and government.[59] ISAs, like EDA tools, are a potential chokepoint for the United States to restrict China's chip ecosystem. However, despite excitement about RISC-V, the Chinese government has done little to support it, devoting a miniscule slice of the tens of billions publicly committed to boosting the domestic chip industry.[60]

In addition to avoiding U.S. export controls, RISC-V represents Chinese firms' first opportunity to be present at the creation of a new ISA, benefitting from the opportunity to develop know-how and products alongside a new technological framework. Chinese firms have struggled for decades to build globally competitive chips. The reset that technological shifts and RISC-V portends gives these firms another chance to take market share from Western leaders.[61]

China is by no means destined to dominate the RISC-V space. As Saifang Technology CEO Xu Tao said in a recent interview, "the Chinese ecosystem's main shortcomings with regards to RISC-V are

59 Li Yuan, "ZTE's Near-Collapse May Be China's Sputnik Moment," *New York Times,* June 10, 2018, https://www.nytimes.com/2018/06/10/technology/china-technology-zte-sputnik-moment.html.

60 Anonymous interviews with participants in the Chinese RISC-V ecosystem, November 2020.
Kevin Xu, "China's Semiconductor Future: What Can $1.4 Trillion Buy?," *The Wire China,* October 4, 2020, https://www.thewirechina.com/2020/10/04/chinas-trillion-dollar-investment-and-semiconductor-future/.
Yoku Kubota, "China Sets Up New $29 Billion Semiconductor Fund." *Wall St. Journal*, October 25, 2019.https://www.wsj.com/articles/china-sets-up-new-29-billion-semiconductor-fund-11572034480

61 As Saifang Technology CEO Xu Tao said, "Although the RISC-V ecosystem is small, because it is small, Chinese manufacturers may have opportunities for development." Lai Shasha, *RISC-V Wants to Share the World with Intel and ARM.* RISC-V欲与英特尔、ARM三分天下. Yicai, January 14, 2021. https://web.archive.org/web/20210212190700/https://www.yicai.com/news/100914236.html

on the talent, software, and application sides."[62] Its firms, like the rest of the world's, lack talent with deep experience in the ISA, though universities are rolling out new teaching materials and conducting RISC-V competitions, and the fifteen thousand who tuned into a recent RISC-V livestream of a conference on the mainland testifies to broad interest. As Xu Tao explained,

> *"China has never had a real success story when it comes to building a software and application ecosystem... particularly when it comes to basic software like compilers, debuggers, an OS, basic libraries, upper application frameworks, and so on. There are gaps in the overall contribution of similar software, but the current growth is relatively fast. Many domestic companies have continued to improve such software, and the gap is narrowing step by step."*[63]

Other emerging economies could gain from RISC-V's potential to reshape the industry, too. The Indian government has invested in developing a series of indigenous processors, with IIT-Madras' Shakti program leading the way.[64] The hope is that a more commoditized industry will undercut premium pricing for processors, upending the semiconductor market and turning the industry into more of a services business. Indian firms, already world-class service providers, could then leverage the country's electrical engineering talent to compete with the global players on everything outside the highest-end chips.[65]

SHOULD THE U.S. FEAR RISC-V?

Some within the U.S. government fear Chinese firms' eagerness to adopt RISC-V. Given that open-source software enabled the rise of Chinese internet tech giants like ByteDance and Tencent, some think RISC-V could presage similar dynamics in the hardware space, whereby Chinese firms backed by government subsidies could capture the domestic market. RISC-V could replace Western intellectual property. In such a case, chip design could become more of a commodity whereby China's scale and capacity for subsidies could flood the global market. Serge Leef, a DARPA microcontroller product

62 *Can the Open Source RISC-V be the Antidote to China's "Chip Deficit"?* Recode, 开源的RISC–V能否成为中国"缺芯"的解药？Pingwest, January 18, 2021.

63 Ibid.

64 "Shakti Open Source Processor Development Ecosystem," Shakti, 2020, https://shakti.org.in/.

65 Interview with G S Madhusudan November 30, 2020.

manager, argued in January 2021 to the *Wall Street Journal* that RISC-V could be "giving China a leg up on all these technologies because they can now save 20 years of engineering and catch up to Western technology overnight? It's not unlikely."[66]

In early 2020, the RISC-V Foundation reincorporated from the United States to Switzerland in a bid to "calm concerns of political disruption to the open collaboration model."[67] Although the announcement was praised by firms like Huawei, the move doesn't guarantee that RISC-V will stay outside the reach of U.S. export controls. If the U.S. government was determined, regardless of the Foundation's domicile, it could very well put much of the intellectual property out of the reach of Chinese members, or at the very least fracture the Foundation such that U.S. firms could no longer contribute to the community and have to start their own independent line of the project. That said, many U.S. firms are likely to lobby to keep RISC-V open, as only Arm and Intel would potentially gain from an aggressive export control policy directed at the ISA.

Though some in Washington fear RISC-V, the United States has much to gain from RISC-V—if it can take advantage of the opportunity that open-source hardware provides. Open-source software powered the rise of today's American software giants.[68] While the rise of RISC-V would lower the price of chip design and lead to commoditization in some areas in the semiconductor industry, it would shift the key point of competition from capital to design creativity. This would play to America's strengths as the global leader in producing high-end engineering talent and matching it with business acumen. What's more, so long as open-source EDA tools are a long way off, the United States will still have a choke point to

THOUGH SOME IN WASHINGTON FEAR RISC-V, THE UNITED STATES HAS MUCH TO GAIN FROM RISC-V—IF IT CAN TAKE ADVANTAGE OF THE OPPORTUNITY THAT OPEN-SOURCE HARDWARE PROVIDES

66 Asa Fitch, "China's Chip-Independence Goals Helped by U.S.-Developed Tech," *Wall Street Journal*, January 11, 2021, https://www.wsj.com/articles/chinas-chip-independence-goals-helped-by-u-s-developed-tech-11610375472.

67 "History of RISC-V," RISC-V, 2020, https://riscv.org/about/history/

68 Joel Hruska, "We've Never Seen Intel Struggle Like This," *Extreme Tech,* July 27, 2020, https://www.extremetech.com/computing/313208-weve-never-seen-intel-struggle-like-this.

squeeze Chinese firms for a long time. Moreover, U.S.-based SiFive is today best-positioned to develop a leading role in the global RISC-V ecosystem among new chip companies.

So what should the United States do to invest in the open-source hardware paradigm? First, the country should put in place a policy of "do no harm," and instead encourage more development and growth of this important sector. It should subsidize additional research at university and industry research labs, encourage and underwrite student training in this new space, and work to build a handful of centers of excellence that not only propel the technology forward, but also connect researchers and academics to industry.DARPA has a role to play in pushing out the technological frontier. However, as one DARPA project manager said in relation to RISC-V, "DARPA funds projects not infrastructure."[69] To support the broader ecosystem to revitalize the domestic chip industry, the United States needs investments in companies that are willing to look on a longer investment horizon than Silicon Valley has for a return. For the past 20 years, American VCs have been less interested in semiconductor startups, citing their high startup costs and low growth in the industry. Given that firms (like Redhat) based on open-source technologies have taken a long time to mature, government could do more to invest in building out this ecosystem. Congress should consider earmarking funding for open-source hardware technologies.

69 Linton G. Salmon, "A Perspective on the Role of Open-Source IP In Government Electronic Systems," Defense Advanced Research Projects Agency, November 29, 2017, https://riscv.org/wp-content/uploads/2017/12/Wed-1042-RISCV-Open-Source-LintonSalmon.pdf.

CONCLUSIONS

With the U.S. semiconductor industry facing intensified competitive pressure—and with computer chips playing a fundamental role in America's accelerating technology competition with China—policymakers are taking chips more seriously than they have in decades. Today, semiconductor shortages are impact supply chains for goods like autos. Yet, discussion about risks to America's semiconductor sector are too focused on specific subsets of the industry at the expense of the broader ecosystem. On top of this, U.S. debate too often turns toward how to defend existing advantages rather than how new innovation can shift existing paradigms.

Congress and the Biden administration are considering ways to support the industry. The history of the industry suggests that trying to subsidize specific firms or today's technologies is likely to fail. The government is not going to have better knowledge than semiconductor industry experts themselves about the future of technology. And industry experts themselves disagree about how chips will develop over the next decade. The industry simply moves too fast for Congress or the White House to pick winners or to understand the technology trajectory with enough granularity.

Rather than trying to protect specific firms or to acquire a defined set of technological capabilities, the government can help by supporting a healthy semiconductor ecosystem, including a well-trained workforce; an amply-funded venture capital environment, especially for early-stage firms; and an educational system that fosters new and disruptive ideas. The U.S. government has a long track record in playing this role, from the invention of the first chips. Research into next-generation technologies; fostering partnerships between government, universities, and companies; and using existing government bodies like DARPA and In-Q-Tel to support microelectronics are ways that Washington can bolster the chip industry without trying to take major bets on specific companies.

Some in industry and in Congress have advised spending billions of dollars subsidizing the construction of new manufacturing facilities ("fabs") in the U.S. Given that the most advanced new fabs can cost up to $20 billion to build, this is not a cost-effective strategy. For example, during the 1980s, the investments in university research centers that seeded U.S. dominance in the sphere of electronic design automation cost tens of millions, not tens of billions. It is these investments that help make U.S. export controls on China effective today. The other "chokepoint" technology that the U.S. current controls is in semiconductor manufacturing equipment, a subset of the semiconductor sector that has attracted far less public attention than chipmakers themselves. But for U.S. foreign policy, manufacturing equipment is no less important.

Subsidizing the construction of fabs will certainly boost the semiconductor industry, providing more semiconductor jobs and strengthening the ecosystem. But policymakers must ask whether, given limited resources, this is the best way to accomplish this goal. The two leading chip manufacturers, Samsung and TSMC, are both foreign companies, so even if they agree to set up new facilities in the U.S., their core technology and R&D will continue to take place mostly abroad. Moreover, the leading U.S. chip manufacturer, Intel, is already highly profitable and already produces many chips in the U.S. It has reported billions of dollars even profits during the period in which it lost its manufacturing edge to TSMC and Samsung. Lack of funding wasn't the cause of its technological issues, so government financial support probably won't be the solution. It would be smarter for the U.S. government to consider how it can support Intel's efforts to expand potential growth markets, such as chips needed for O-RAN telecoms technology.

A final recommendation for policymakers is to take a sophisticated approach to open-source software. Some media reports have characterized open-source as a tool for China to undermine U.S. intellectual property or market dominance. In fact, the U.S. could be the greatest beneficiary of increasing use of open-source architectures if this unlocks new creativity in chip design, a segment in which the U.S. plays a leading role. Government can be supportive by seeing open-source not as a threat but as an opportunity, and helping to educate a workforce that is familiar with open-source designs.

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