OF SWANS AND RHINOS:

Building Resilience in the Semiconductor Supply Chain

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Wilson Center

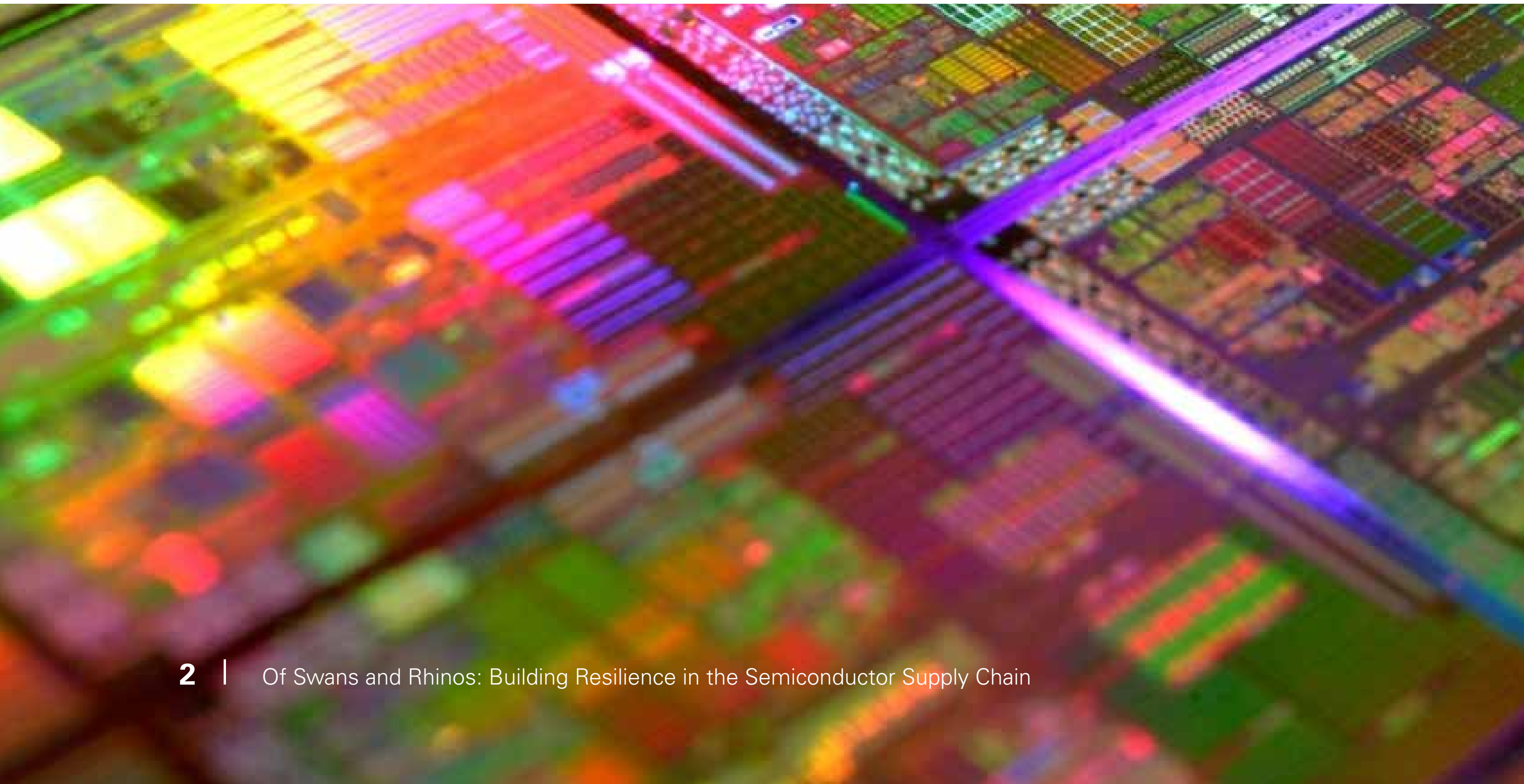
SUPPLY CHAIN INITIATIVE

Executive Summary

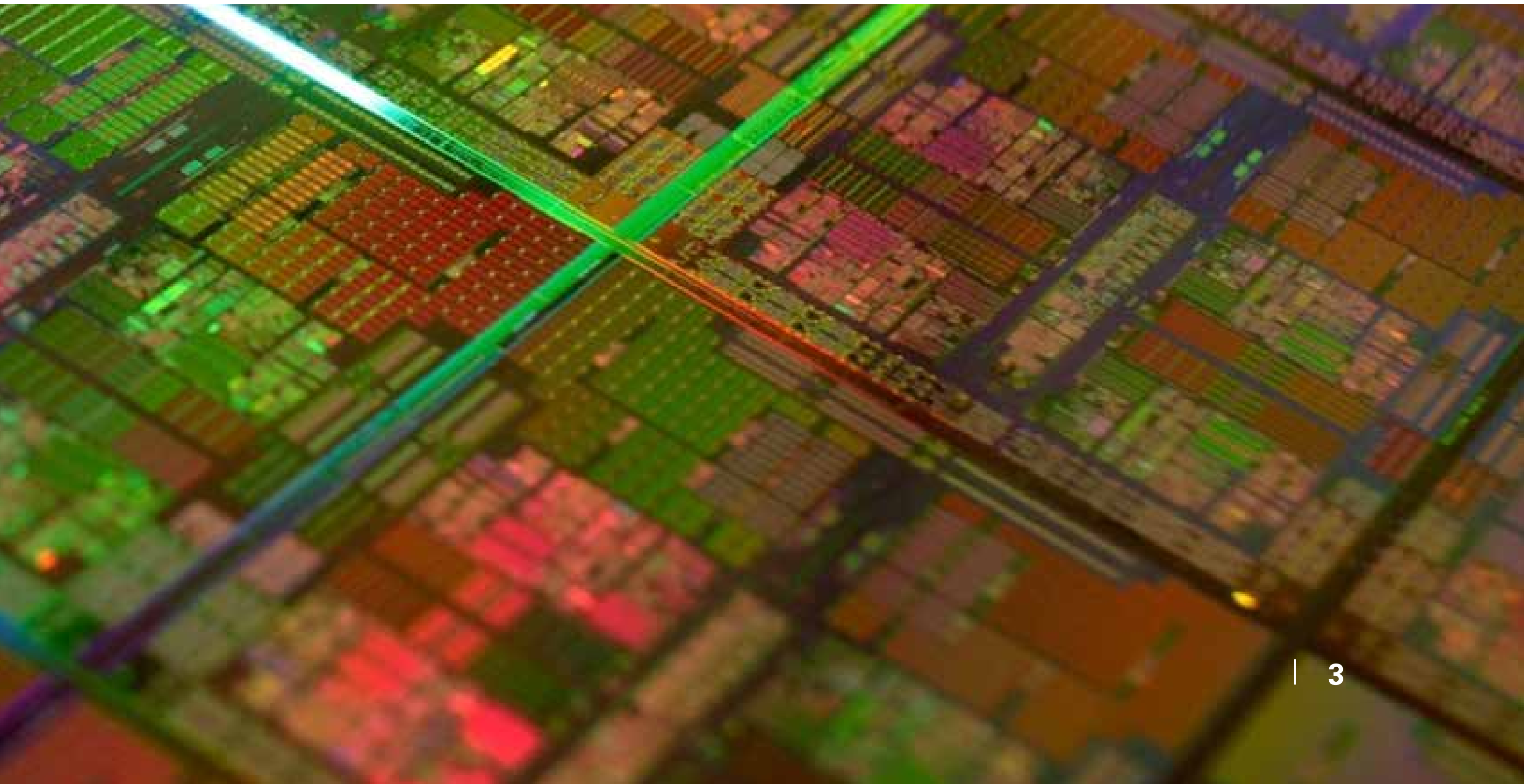
As semiconductor supply chains rebound after two years of disruption, the United States has taken important steps toward building resilience in the sector over the coming years. The CHIPS and Science Act of 2022 allocates significant funding to incentivize private sector investment in the US semiconductor industry, as well as major long term commitments to strengthening R&D and STEM education. This paper examines the challenges of the semiconductor supply chain, the advances made by the CHIPS and Science Act, and by private companies in analyzes the remaining long-term challenges faced by both the US government and the private sector. Central to the analysis contained here is an understanding of both Black Swan and Gray Rhino risks: the challenges we don't see coming and those that we see on the horizon but act on too slowly.

The major takeaways of this report by the Wilson Center include:

- The semiconductor industry plays a growing and increasingly critical role across the economy, creating the potential for a damaging "domino effect" when disruptions occur.
- This means that short- and long-term actions must be taken to make the supply chain more resilient.
- There is an urgent need to prepare for and manage unpredictable as well as predictable exogenous shocks across the supply chain.
- The federal government must play an increasingly prominent and hands-on role in the semiconductor industry.



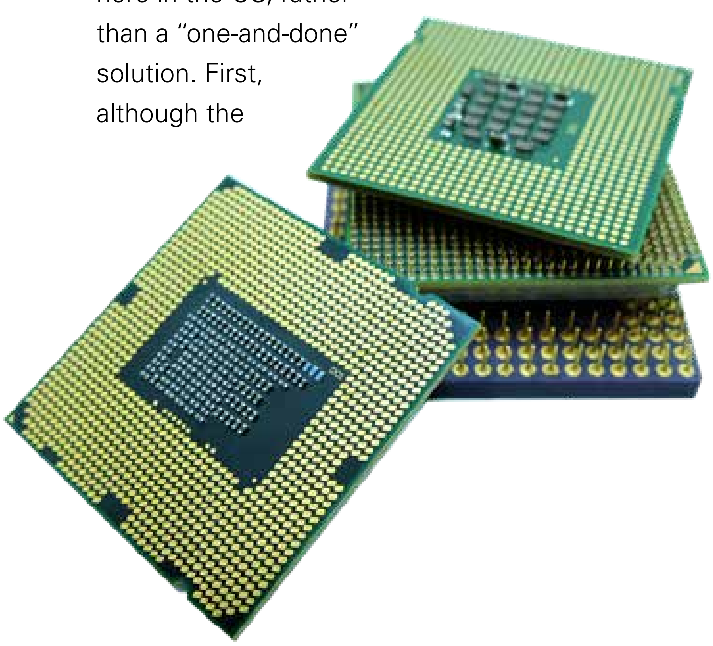
- Better planning and coordination is needed to predict future demand patterns so that capacity can be ensured to meet demand and there is an urgent need for improved understanding of the minimum fab capacity required for national security reasons.
- Diversification of the geographic footprint of the global supply chain is needed to mitigate risk stemming from over-concentration of fab capacity.
- To protect the US lead in advanced semiconductor R&D, government actions must both lower the costs of production in the US, and fund future research.
- Reshoring fab capacity to the United States is an essential part of the solution, alongside the phenomena of ally- and friend-shoring.
- From the industry perspective, reducing emissions, using renewable energy sources and reducing energy intensity provide a win-win proposition, diminishing costs, increasing certainty and improving ESG compliance.
- With shifts in the distribution of water resources due to climate change, government and industry must look to investing more heavily in modern water infrastructure.
- Human capital shortages require substantive plans and legislation to fund training, education, and workforce development programs, with a particular focus on diversity.
- Despite a complicated bilateral relationship, the US and its allies should try to engage with China to develop a more complete understanding of the global semiconductor supply chain and its implications for US industry and manufacturing.



Introduction: A Strategic Vision for Semiconductors

The United States faces a severe threat to the competitiveness of its economy and its national security without urgent action to drive investment in the semiconductor sector here at home and in allied countries. Fortunately, many decision-makers across government and industry recognize the need to strengthen the semiconductor supply chain and are taking steps in the form of official reviews, studies by industry, and, most importantly, legislation in Congress.

After much delay, in July 2022 the US Congress approved a $52 billion package of support for the semiconductor industry, aimed at boosting domestic production as well as R&D in the sector. The CHIPs and Science Act of 2022, includes more than $52 billion for US companies producing computer chips, as well as billions more in tax credits to encourage investment in chip manufacturing. It also provides tens of billions of dollars to fund scientific research and to spur the innovation and development of other US technologies. It is vitally important that this is seen as a first step to a longer-term strategy to promote the industry here in the US, rather than a "one-and-done" solution. First, although the $52 billion contemplated in the CHIPs and Science Act is positive, and will certainly help, it is not a huge amount when compared with the funds being invested by the private sector and by Asian and European governments. Second, policy-makers and industry leaders must focus not only on short-term incentives to attract investors, but more importantly on the long-term, and "over-the-horizon" challenges such as environment, energy, and human capital. The struggle for resilience in the semiconductor supply chain will be won through attention to the fundamental elements of 21st century competitiveness.



This paper will focus on the need for a strategic vision for the semiconductor industry, which takes into account recent supply chain woes, as well as the over-the-horizon risks facing the industry. While the immediate challenge of semiconductor shortages is being addressed with concerted action by government and industry, the long-term geopolitical, energy, water, and human capital challenges remain stubborn and poorly understood by policymakers. This paper calls for industry and government to work together to find a strategic approach to the semiconductor sector that will bolster both competitiveness and national security by increasing the resilience of the supply chain.

Background

The onset of the COVID-19 pandemic in 2020 brought into high relief a number of fundamental vulnerabilities in America's supply chains, affecting products and services across the spectrum of the economy, and forced policymakers, business strategists, and ultimately, consumers themselves to question the merits of a globalized manufacturing platform formed of complex and intricate relationships across national borders and regions. In the United States and many other countries, the language of reshoring and near-shoring became commonplace as economic nationalism surged in the face of external threats.

For the past two years, news headlines have focused specifically on the way the semiconductor shortages have created serious problems for the automobile industry, though microchips have become an essential component in much more than cars. From smart TVs to coffee makers, from fridges and washing machines to laptop computers, and from home security systems to robotic vacuum cleaners, contemporary life in the developed world has become highly dependent on the supply of chips to the factories that produce modern consumer goods.

The semiconductor industry stands out as an example of an economic sector that has advanced over the past half century largely because of the increasing specialization of functions among different countries and regions of the world, highly effective industrial policy, and implications for geopolitical and geoeconomic goals. For example, the cumulative effect of decades of government incentives and investments in facilities, research and design, and human capital by certain Asian economies has allowed them to become world leaders in areas of advanced semiconductor manufacturing. It would take years, if not decades, for the United States, Europe, and other parts of Asia to replicate this success. However, within the globally integrated manufacturing system the United States has been able to build and maintain an impressive lead in the R&D and design-intensive activities of the global chip ecosystem.

As the chip shortage deepened in 2020 and 2021, industry and government engaged in an in-depth analysis of the semiconductor supply chain, identifying existing problems and putting forward proposals to provide short and long-term relief from the problems affecting many areas of the economy. The Biden administration included semiconductors in its 100 Day and One Year Reviews of America's supply chains.[1,2] What became clear through these various studies and reports is that both manufacturers and society in general have become highly dependent on globalized semiconductor supply chains that depend on specialized production in a small number of locations, exposing the system to significant risk. When times are good and manufacturing and logistics function as intended, the benefits of this global division of labor are abundant and shared by many. However, an exogenous shock, such as the COVID-19 pandemic, can result in massive and long-lasting disruptions to modern manufacturing and therefore of the reliable supply of consumer goods to the marketplace. The potential for disruption necessitates a diversification of the supply chain.

While the drive to bring manufacturing back home may make sense in some sectors, this does not hold true for all areas of the economy. When we examine the semiconductor supply chain, despite recent investment in new fab capacity here in the US, it becomes clear that some parts of the value chain are resistant to reshoring. For example, it would be expensive and logistically challenging in the short term to repatriate many of the functions of raw materials extraction, processing, and refining, as well as some advanced manufacturing functions. In the case of raw materials, many of the precious metals used in chip production are not found in the United States and their processing and refining is concentrated in a small number of countries.[3]

In early 2022, the Wilson Center convened a high-level group of industry representatives, policymakers, and independent experts to examine the vulnerabilities impacting the semiconductor supply chain. Rather than replicate efforts underway in the government, other think tanks, and industry associations which focus on the immediate problems afflicting the supply chain, the Wilson Center working group focused on long-term, "over-the-horizon" issues to provide a complementary perspective.

Two key takeaways emerged from these dialogues. First, it is clear that the narrative on global supply chains is changing in fundamental ways. From a focus on reducing costs and maximizing efficiency, there has emerged a growing emphasis on sustainability, social license, resilience, and geopolitical considerations.

Second, it became apparent that there are certain risks that are unfolding in real-time, but which have not received sufficient attention in the various studies driven by COVID-induced disruptions. The working group discussed water, energy, and human capital inputs as well as geopolitical and other exogenous and systemic shocks. Although the list of these risks is far from complete, the dialogues afforded insights into the nature of the long-term vulnerabilities of the supply chain and the need to address them with clarity and pragmatism. What is needed is a strategic approach to our nation's semiconductor industry, one that recognizes present and future challenges, and one that recognizes the sector's core role in America's national security and economic competitiveness.

The Evolution of the Supply Chain Paradigm: A New Focus on Resilience

The post-WWII international economic order, focused on the importance of free trade, facilitated the emergence of a system of production in which intra-firm and intra-industry trade became integrated across borders. The end of the Cold War in the early 1990s, along with the increasing freedom of capital, further facilitated this process by opening up new markets that had previously been closed to Western investors. Hyperglobalization, with an emphasis on reducing production costs, brought the relocation of production facilities around the world, often far from the final assembly location. China rapidly became a manufacturing and export powerhouse, and the Chinese and US economies became increasingly intertwined.

However, over the past decade or so, values-based concerns around environment, sustainability, social and labor issues, and corporate governance/anti-corruption have also become important drivers of investment decisions. Environment, social, and governance (ESG) concerns have become a key consideration in determining capital flows from both individual and institutional investors alike.[4] Concerns over climate change and the desire to mitigate its impact has been one of the most important factors in reshaping capital flows alongside concerns over labor standards (especially with regards to forced and child labor).[5]

Meanwhile, severe disruptions in global supply chains caused by the COVID-19 pandemic rapidly became a determining factor in the reorientation of global manufacturing of certain items. Security of supply in the face of public health, as well as logistical and infrastructure limitations, called the reigning system of globalized production into question. Reshoring, nearshoring, and ally-shoring concepts that had begun to have resonance in public policy circles during the Trump administration, acquired new relevance and urgency in the face of the pandemic. This has become even more important given ongoing disruptions to the Chinese economy brought about by the Xi government's zero COVID policy.[6]

More recently, the Russian invasion of Ukraine in February 2022 renewed geopolitical concerns over globalized manufacturing and supply chains. The flow of oil and gas, food, and certain critical minerals were interrupted by the outbreak of hostilities caused by the Russian invasion and analysts immediately began to consider the implications of conflicts elsewhere in the world, especially a potential Chinese military action against Taiwan. The application of sanctions to the Russian economy and the severe disruptions brought about by the conflict in Ukraine have added a sense of urgency for the private sector to include geopolitical trends along with their inherent risks and opportunities. Great power rivalry with China and the risks of escalation in already tense trans-Pacific relations, raise the specter not only of Chinese actions against Taiwan, but also the growing prevalence of geopolitical concerns in US foreign economic policy.

This evolution of supply chain considerations has immediate implications for the semiconductor industry. The sector has grown and evolved over the past few decades to become one of the most globalized industries ever seen (see below) and has developed a system of cutting costs but also taking advantage of R&D excellence, local talent sources and expertise, and of course, government policies that have incentivized the industry in different national jurisdictions. At the same time, we have seen the concentration of specific aspects of the industry (such as wafer production or advanced nodes) in specific countries and regions. This concentration of functions has led to potential bottlenecks and vulnerabilities. As these vulnerabilities have become more apparent, and as geopolitical concerns have grown in the aftermath of the Russian invasion of Ukraine, questions have emerged over the emphasis on globalization strategies.

The combination of factors such as cost, location, environment, society, governance, security of supply, and geopolitics must somehow be combined in contemporary thinking and policy in such a way as to increase the resilience of the supply chain. Companies and governments must consider a wide range of factors that impact upon their manufacturing production models and must begin planning now for risks that will play out in a decade or more.

> **By "resilient," we mean not the elimination of risk in the supply chain,** but rather the capacity to react, pivot, and bounce back if and when that risk becomes a reality. Resilient ecosystems in nature are those that are able to survive exogenous shocks; resilient communities are those that can bounce back after outbreaks of crime, violence, or a natural disaster. It is the same for supply chains. If we plan correctly for the future, as uncertain as that is, we can both reduce risk and be better prepared to react and respond if and when supply chains are disrupted.

A Complex and Dynamic System: The Global Semiconductor Supply Chain

Semiconductors have become an essential component of modern life. Their near ubiquity has transformed our existence and to fully grasp the scale and nature of the vulnerabilities affecting the semiconductor supply chain, it is vitally important to understand its complexity. Perhaps more than any other sector, the semiconductor supply chain has evolved to be highly complex and hyper-globalized with an elevated level of specialization. From inputs to the manufacturing process, to its dependence on human capital, innovation and geopolitics, to the rapidly expanding use of semiconductors in everyday products, strengthening the semiconductor supply chain presents a herculean challenge that will not be resolved with any single approach. An integrated, multidimensional strategy that recognizes the short-, medium- and long-term challenges, as well as the rapidly changing nature of the industry, is essential.

Due to the increasingly technological nature of warfare, as well as the growing importance of the telecoms industry and the internet of things (IOT), it is expected that the sector will continue to grow, and with recent efforts to boost domestic production of semiconductors, exports will grow too. Investment in R&D is critically important in the sector, with a lot of the industry's revenue going back into developing new products. In fact, the semiconductor industry has spent between 15 and 20 percent of its revenues on R&D over the past decade.[7]

From its origins in California in the 1960s, the semiconductor industry has become one of the biggest and most strategically important sectors of the US economy. Semiconductors are the US's fourth largest export product by value, after the automobile, aerospace, and oil industries, and the US semiconductor industry accounts for around 50% of global semiconductor revenue. However, over the past two decades, the share of global semiconductor manufacturing capacity in the US has fallen from 37% to only 12%.[8] This is due to the rise of the semiconductor industry overseas, in particular in countries such as Taiwan, Korea, and China, and the incentives their governments have put in place to attract investment. In fact, government incentives range from 45-70% of the cost advantage in these countries.[9] The US continues to lead in the R&D intensive stages of chip fabrication, where most value is added, and has a strong presence in the production of semiconductor manufacturing equipment, but incentives strategies by other governments have led to a growing dependence and vulnerability to overseas suppliers. In both fabrication of semiconductors and assembly, testing and packaging (ATP), the US has fallen far behind. Foreign producers also dominate the materials side of the semiconductor supply chain, notably in silicon wafers, photomasks, and photoresists.

Canada

Canada is an attractive destination for the world's largest semiconductor designers and producers due to its well-educated workforce and growing roster of technology hubs. Canada's critical minerals resources and stable legal and political environment have contributed to the recent growth in the sector.

Global industry leaders that have chosen Canada for early-stage semiconductor value chain operations like research and design include TSMC, Intel, Samsung Electronics, IBM, Teledyne, and Qualcommoperate facilities in Canada.[10] Bromont Science Park in Quebec is home to IBM's largest semiconductor assembly and test facility in the world; according to the company's website, "[e]ach server developed by IBM contains at least one component built inside the Bromontplant."[11] Nearby, Teledyne DALSA operates a foundry that specializes in chip components for digital imaging products.[12]

Canada's significant automotive, aerospace, agricultural, life sciences, and wireless telecommunications sectors create local demand for semiconductors and photonics, and a testbedfor applied innovation. To serve these customers Canada has more than 30 applied research laboratories and 5 commercial facilities specializing in compound semiconductors, microelectromechanical systems (MEMS) and advanced packaging.[13]

Canadian engineering programs rank competitively amongst top universities in the United States, United Kingdom, and China: three Canadian schools – University of Toronto (34), University of British Columbia (36), and University of Waterloo (39)– ranked in the Top 50 of the 2022 QS World University Rankings for Engineering and Technology.[14] Interest in engineering and STEM programs is also rising: from 2014-2018, enrolment in Canadian mathematics, computer, and information science programs increased by almost 50%.[15]

Canada is rich in critical minerals – specifically gallium and tellurium – that are essential inputs for semiconductor components.[16] The country's freshwater resources, which constitute 20% of global supplies, are support water-intensive semiconductor production processes[17]. Canada's track record in environmental and social governance standards setting and reporting transparency is an asset in sourcing sensitive natural resource inputs.

Canada is positioning itself for a larger role in the semiconductor supply chain. A February 2022 announcement of federal support for semiconductor and photonics research and development confirms federal support for growth.[18] The Semiconductor Industry Council of Canada, established in 2021, forecasts significant growth in Canada's semiconductor sector through 2050.[19]

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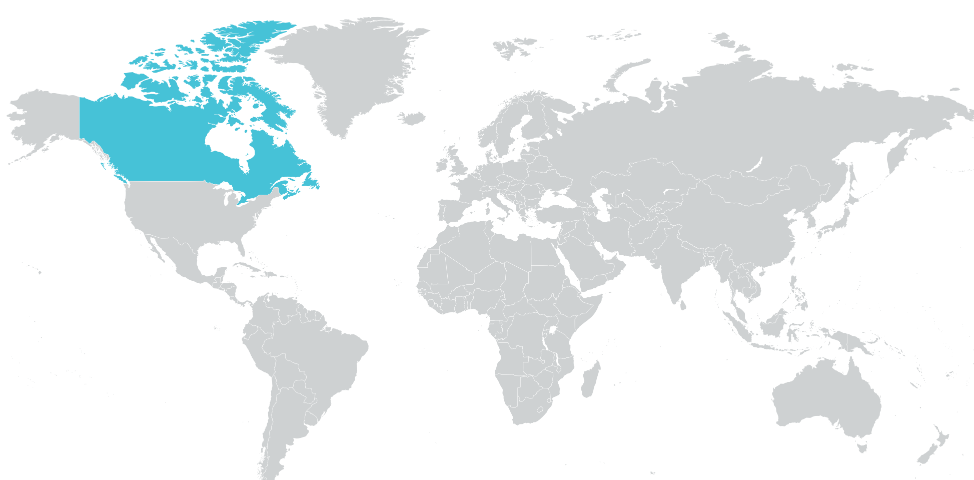


Much of the recent attention in the media and among policymakers has fallen on chip manufacturing at the most advanced process technology nodes (10nm and under). While the supply chain challenge is indeed acute in this area, it is important to remember that demand growth continues to be strong for semiconductors fabricated using intermediate (14nm to 45nm) and mature (65nm and above) node process technology. Deloitte predicts that production growth is indeed strongest for the most advanced nodes at 24% in 2022, whereas for intermediate nodes growth will be 14% and a 9% growth in mature nodes.[20] However, continued strong demand growth for semiconductors produced using intermediate and mature nodes highlight the fact that businesses and policymakers must be concerned about supply shortages across the industry.

Chips used in automobile electronics, for example, need to be more resilient to harsh conditions such as heat, vibration and many hours of operation over long periods.

This makes certain larger diameter node production processes the best option but the fact that these chips are seen as "less advanced" due to their size does not make them any less important. If the chip is not available when the car is ready to be fully assembled it can shut down entire lines and plants and impact entire communities.

To the untrained eye, one chip may appear to be much the same as another. However, there is a high degree of specialization and chips are rarely interchangeable. For example, in automotives, semiconductors that are installed to maximize fuel efficiency are completely different from those that are used to regulate interior temperature in the cabin of the vehicle. The chips used to manage the safety features in turn are different from those used to run the entertainment system.

Not only is the semiconductor supply chain complex, but it is highly dynamic, regularly undergoing profound changes.

Not only is the semiconductor supply chain complex, but it is highly dynamic, regularly undergoing profound changes. This is due in large part to two factors: technological progress and dramatic increases in demand. Moore's law (the principle that the number of transistors a semiconductor contains doubles every 18 to 24 months, and as a result the power and functionality of the end devices enabled by semiconductors doubles) brought about a rapid growth in processing power; although the rate of doubling has slowed in recent years, ongoing improvements and increases in processing power mean that we continue to see impressive advances in the sector, and with them ample scope for specialization.[21] The data published by SEMI shows the growth in demand for all types of chips in the coming years, with the global semiconductor market growing from $342.7B in 2015 to $655.6B in 2025 (an annual growth rate of 6.7%).[22]

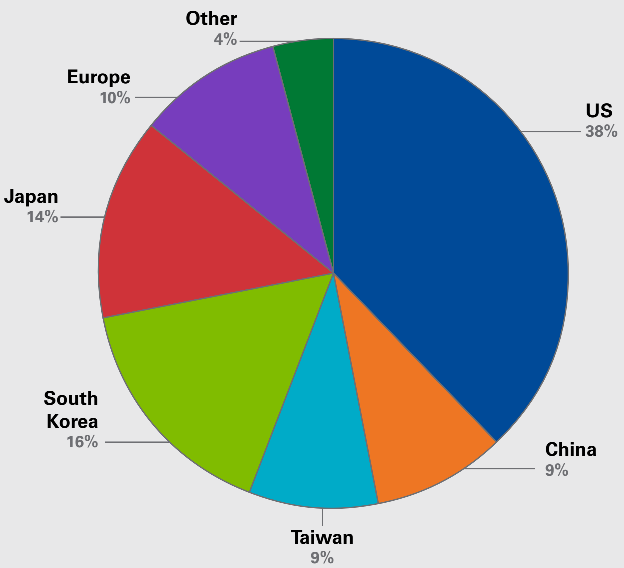
In part because of this specialization, we are also observing an exponential growth in demand for semiconductors as products of all kinds incorporate chips for a wide variety of functions. One of the most important drivers at the current time is connectivity, as the Internet of Things (IOT) and the development of 5G technologies (smart phones in particular) bring a huge boost to demand. With connectivity comes a greater flow of data, and a need for low power consumption. Demand for IOT-related semiconductors and sensors is predicted to grow by an annual rate of 15.3% until 2025, reaching a total of more than $114bn.[23]

At the same time, the increased use of semiconductors in the automobile industry is being further boosted with the rise of driver assistance systems (such as intelligent cruise control, self-driving and early warning systems). Increasingly these features are becoming standard, and the "smart" features of a vehicle are seen as a competitive advantage. Industry research also highlights that, while the United States and Europe have been driving demand growth in the semiconductor market for many years now, China is rapidly catching up and will become one of the most important drivers of demand growth in the near future, particularly as 5G is built throughout the country.[24]

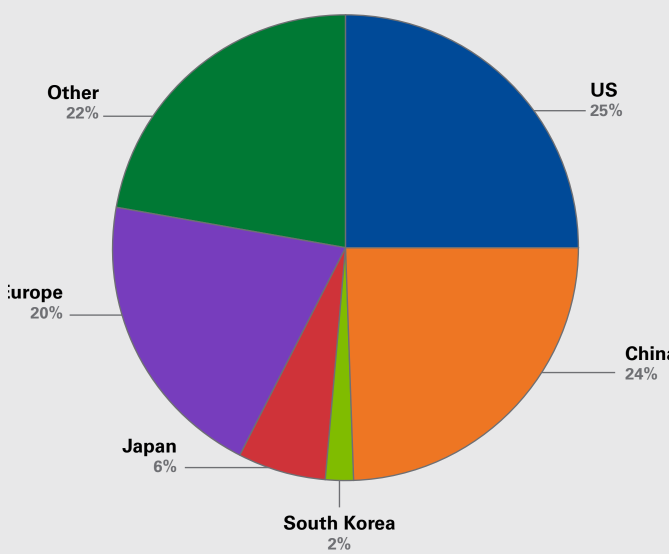
Fab or Fabless?

In addition to the dizzying array of semiconductors satisfying a myriad of functions, it is vital that we distinguish between the manufacturers who produce chips in their own factories or "fabs" and those who are "fabless." The 2019 book of the same name made the point that the existence of semiconductor "foundries," that is fabs that produce chips for other manufacturers, had allowed for a dramatic expansion of production as excess capacity within fabs was employed to satisfy demand from diverse sectors.[25] By 2019, 20% of all chip production took place within foundries. The success of countries such as Taiwan has, in part, stemmed from their fabs acting as providers of semiconductors to industries all over the world. Indeed, the Taiwan Semiconductor Manufacturing Company (TSMC) describes itself as the "world's dedicated semiconductor foundry."[26] The existence of companies such as TSMC allows other semiconductor manufacturers to focus on the design of

The Global Semiconductor Industry: Overall Share of Value Added by Country/Region



Semiconductor Consumption by Country/Region



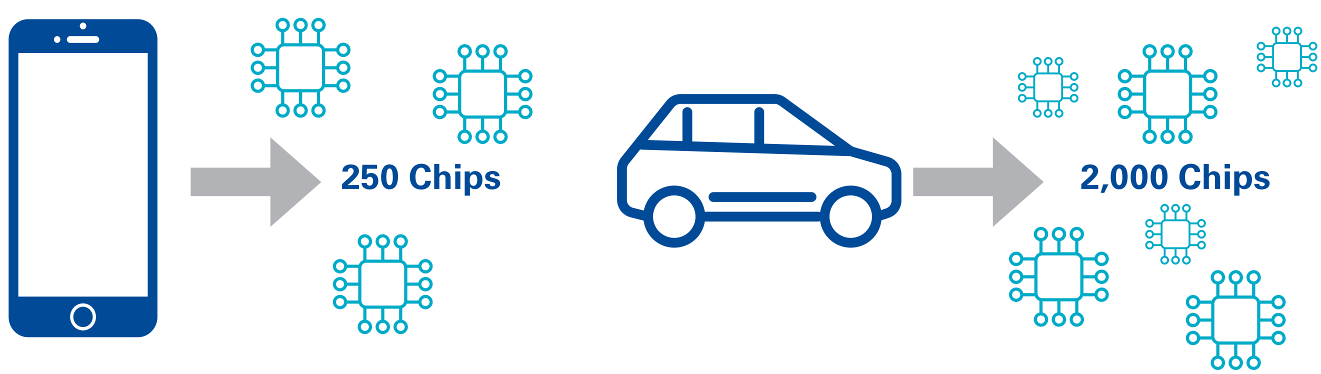
Data taken from "Strengthening the Global Semiconductor Supply Chain in an Uncertain Era" BCG/SIA[28] new chips and reduce costs by taking advantage of existing fab capacity elsewhere. Alongside highly effective industrial strategies implemented by policy-makers and industry leaders in a number of Asian countries, this has contributed to the geographic concentration of certain aspects of semiconductor manufacturing.[27] For this reason, above all others, diversification of semiconductor manufacturing must be a priority for industry and government decision makers.

The growth and Complexity of Semiconductor System

The demand for chips has ballooned in recent years, with rapidly increasing applications in end-use products, including treadmills, thermostats, refrigerators, ATMs, and more. For example, the average smartphone requires more than 250 chips.[29] All newer cars require a whole suite of chips, but an average electric vehicle requires approximately 2000 chips, more than twice as many chips as a traditional vehicle.[30] This substantial increase highlights how the needs, wants, and behaviors of consumers have fundamentally evolved in the years since the semiconductor's original inception - an evolution that will continue to shape the semiconductor industry. The increased prevalence of the semiconductor creates greater risk and consequences to the global supply chain for all these end products in the case of disruptions (as we have seen in recent years in the auto industry).

Though the complexity of semiconductor production and packaging limits countries from dominating end-to-end production, the specialized nature of the industry has resulted in geographic concentration, with different regions of the world specializing in different elements of the production process. Whereas the United States dominates in R&D, design, and equipment, Asia-Pacific leads in terms of foundries, electronics manufacturing service (EMS), and outsourced semiconductor assembly and test (OSAT), and Europe's semiconductor industry dominates with "Core IDM + equipment."[31] According to a report published by Boston Consulting Group and the Semiconductor Industry Association, there are more than 50 choke points in the semiconductor supply chain where one region accounts for more than 65% of the global market share.[32]

For example, 75% of global foundry capacity is located in the Asia-Pacific region and 100% of global foundry capacity for chips less than 10nm is located in Taiwan and South Korea.[33] According to a report published by Accenture, one chip crosses international borders an average of 70 times and requires more than 1,000 regulatory steps before reaching the customer.[34]



Latin America

Historically, Latin America has been a peripheral player in the global semiconductor supply chain, but recent shortages have drawn attention to a potentially greater role for the region in the production of computer chips. The High-Level Economic Dialogue between the United States and Mexico, for example, now includes a semiconductor working group, where senior officials from both countries have discussed the possibility of semiconductor production in southern Mexico. Meanwhile, Brazil's semiconductor industry has attracted $2.5 billion in investment for infrastructure, machinery and equipment and additional capital for research and development. Brazilian lawmakers approved incentives to investment in the industry, and companies are collaborating with universities to make sure there is enough talent to support the expanding sector.

Costa Rica's computer chip industry is also expected to grow rapidly in the coming years. In 2021, Intel, one of the world's largest suppliers of semiconductors, announced a $600 million investment in Costa Rica for the assembly and testing of microchips, as well as funding for research and development. Other companies, including Microsoft and Zollner, have also announced expanding chip production and research and development in the country.

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Supply and Demand and Cyclical Volatility

The semiconductor industry is much more time-, capital-, and labor- intensive than most other industries and given the complexity of the semiconductor supply chain, addressing changes in supply and demand is much more difficult. As demand for semiconductors grows and becomes increasingly difficult to predict, the ability to adapt to changes in demand is crucial. Like with any industry, but perhaps on an even greater scale given the highly specific nature of semiconductor inputs, the semiconductor supply chain is fundamentally dependent on the tools and raw materials that are required for production. Even if production is built up and scaled, short supply of raw materials necessary for semiconductor production will cause production limitations and delays, not just for the semiconductors themselves but also for end-use products that cannot operate without them. Moreover, because semiconductors are a highly specific and complex piece of technology, there is minimal flexibility between different sectors, cases, and purposes.

Risks and Vulnerabilities

In its 100-Day review of the semiconductor supply chain, the Biden administration identified seven major risks in the face of the supply chain crisis during the COVID-19 pandemic.

- Lack of US production capability at the most advanced technology levels
- Dependence on geographically concentrated foreign production for mature chips
- Dependence on China for sales revenue
- China's aspirations to lead the semiconductor industry
- Human capital challenges, specifically the "graying" of the workforce
- Rising fab costs
- Developing new manufacturing knowledge

In the aftermath of the successful passage of the CHIPS and Science Act, these risks continue to be present. What has been provided by the legislation is an important start in addressing the challenges here in the United States, but the global semiconductor supply chain will continue to require efforts to strengthen resilience.

Conceptualizing the Risks: Swans and Rhinos

The highly complex nature of the semiconductor industry necessitates interconnectivity in all aspects of the supply chain, from inputs and manufacturing to packaging and installation in end-use products. However, this interdependence is synonymous with increased susceptibility to disruptions. A disruption to one element of the semiconductor supply chain, no matter how minor or isolated it may be – whether it be a fire in a glue factory or severe flooding – can (or as with these historical cases, did) have tremendous impacts on the semiconductor industry and beyond. Increasing globalization in recent decades has resulted in significant interconnectivity across supply chains and semiconductors are no exception. Though this increasing interconnectivity is generally viewed favorably, there are inherent weaknesses, especially when it comes to the concentration of specialized manufacturing capacity in a limited number of locations.

Risks exist on both the supply and demand sides. For example, changing geopolitical dynamics, shifts in government policy, or new uses of technology/products can cause both an increase in demand and shortages of supply. Regional crises, even moderate ones, can have significant impacts on the semiconductor supply chain itself and further downstream. For example, severe flooding in 2011 in Thailand (at the time, the world's second largest producer of hard disk drives) impacted both the automotive and electronics supply chain, resulting in hundreds of deaths, the closure of nearly 200 factories, and scaled back production from companies including Western Digital, ON Semiconductor, Seagate, Toyota, and Honda.[35] Financial crises are potential exogenous shocks that pose a significant risk as the connectivity of the semiconductor supply chain heightens and amplifies the cascading effect that these crises can have. The Asian financial crisis of the late 1990s led to government bailouts of the firms, which then subsequently distorted supply. Geopolitical tensions pose a serious threat to the semiconductor supply chain and though economic nationalist policies have intensified in recent years, it has become clear that no country can be fully self-sufficient when it comes to semiconductors.

As we survey the short- and longer-term risks in the semiconductor sector, it may be useful to utilize a simple classification system that in recent years has been called on to explain different kinds of risks facing business and government. First there are the events that we either cannot, or have a tough time, predicting. These are often referred to as Black Swan events. But we should also be aware of a second category of risk, one that includes challenges that we see coming from afar but are too slow to address or that we address ineffectively. These we will classify as Gray Rhinos.

Risks exist on both the supply and demand sides. For example, changing geopolitical dynamics, shifts in government policy, or new uses of technology/products can cause both an increase in demand and shortages of supply. Regional crises, even moderate ones, can have significant impacts on the semiconductor supply chain itself and further downstream.

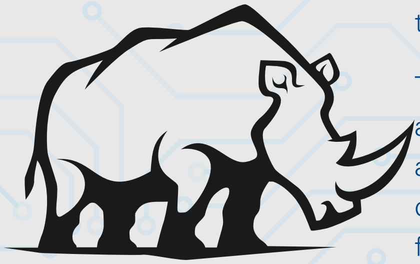
The Black Swan

In 2007, Nassim Taleb published "The Black Swan: The Impact of the Highly Improbable," which explained the importance of unexpected, unpredictable events that cause a massive realignment of expectations for government, business and, society alike. Taleb characterizes Black Swan events by their unique, unpredictable, and unprecedented nature that has significant impact - impact that can be either positive or negative. Black Swan events are characterized by the human response to them, namely the tendency to develop logical explanations and view these events as "obvious" and inevitable in hindsight.[36] Black Swan events, ranging from incredible to catastrophic include: Google's skyrocketing success in the early 2000s, the 9/11 terrorist attacks, and the devastating aftermath of Hurricane Katrina.

Gray Rhinos

Partly in response to Taleb's construct of the Black Swan, Michele Wucker draws on the imagery of a charging rhino in the distance that comes closer and closer until escape from trampling and goring is impossible, Wucker explains:

> "a Gray Rhino is a highly probable, high impact threat, something we ought to see coming, like a two-ton rhinoceros aiming its horn in our direction and preparing to charge. Like its cousin the elephant in the room, a gray rhino is something we ought to be able to see clearly by virtue of its size you would think that something so enormous would get the attention it deserves period to the contrary, the very obviousness of these problematic pachyderms is part of what makes us so bad at responding to them. We consistently fail to recognize the obvious, and so prevent highly probable, high impact crises: the ones that we have the power to do something about."[37]



The Gray Rhino concept is perhaps most obviously and appropriately applied to climate change. In the face of a crisis for which there has been abundant evidence for several decades, whose life-threatening reality comes closer and more obvious year after year, humans have consistently failed to alter their behavior, through a combination of wishful thinking, embedded interests and a perverse incentive structure. However, we can certainly see applications of the Gray Rhino concept in distinct areas of human activity, from the individual level of analysis to those of the corporation, state and the global community.

The Black Swans

Black Swan 1: Geopolitics and Conflict

US-China competition has emerged as one of the defining factors of the modern era. This holds true in the semiconductor space as well, with China making impressive strides in recent years to challenge US dominance of the sector. The Biden administration's review of the semiconductor supply chain emphasized the strategic investments that China has made in recent years, both as part of a comprehensive strategy to develop an indigenous semiconductor manufacturing capability, and to buy up facilities in other countries. In 2019 alone, China announced over $215 billion in investments in new fabs, with heavy subsidies and financing from the government.[38]

These numbers suggest not only a Chinese desire to challenge US (and Taiwanese) dominance of the semiconductor industry, but also prepare the way for a potential decoupling between China and the US. Chinese policymakers, like their counterparts in the US, clearly see that the breakdown of economic integration between the two economic superpowers is a distinct possibility, and they do not want to be dependent on foreign sources.

Even more concerning is the potential for disruption from open conflict. In the post-Cold War period, geopolitical risk receded in the minds of many decision makers in both the corporate world and that of economic policymaking. The absence of major power conflict, the unrivaled dominance of the United States in the face of the collapse of the Soviet Union, and free flow of capital across borders suggested a world in which rivalry between the great powers would be restricted to the realm of economic competitiveness. The deceptiveness of that suggestion became clear with the terrorist attacks of 9/11 in the United States and subsequent terrorist acts across Europe and beyond. At the same time the failure of the WTO to significantly advance a free trade agenda suggested that the world was reaching the limits of globalization.

In 2022, the reemergence of open conflict in Europe with the Russian invasion of Ukraine has exposed the very real risk to the transnational integration of production. The conflict in Ukraine has brought severe economic sanctions against Russia and has also resulted in the interruption of exports of energy, food, and certain critical minerals. For the semiconductor industry, the Russian invasion helped to cast a new focus on the possibility of Chinese military action against Taiwan. Having experienced severe disruptions due to the COVID-19 pandemic, government and industry in the United States and Europe finally began to focus on the potential for chaotic conditions, were China to attack or blockade Taiwan. The aggressive military exercises and posturing by China in the aftermath of Speaker Pelosi's visit to Taiwan in August 2022 only serves to emphasize this particular risk.

However, Taiwan is just one of the potential geopolitical hot spots of concern to the semiconductor industry. Disruptions of major shipping routes or the interruption of key raw materials due to armed conflict, economic sanctions, or heightened geopolitical tension are all considerations driving decision makers in both public and private sectors to consider reshoring, near-shoring, and ally-shoring of the supply chain.

Nonetheless the biggest challenge to globalized manufacturing of semiconductors remains the risk of heightened tensions between China and the United States. Taiwan's dominance in the semiconductor supply chain has left few alternatives for diversification in the short-term, but the urgency of the situation is undiminished. The erosion of the US-China relationship and the growing prevalence of nationalism and nativism in US foreign economic policy poses an existential challenge to an industry that has been driven by a globalist approach to growth.

US-China competition is fierce in the semiconductor space. According to BCG, the US has utilized export controls in recent years as a key element of strategic competition with China, enforcing sanctions and restrictions to limit China's development of advanced semiconductor capabilities. Current US policy restrictions primarily focus on advanced technology for both civil and military uses (such as 5G, AI/HPC chips, and equipment for <10 nm fabs used for advanced logic processors), though the overall policy framework to this approach still remains unclear. China, on the other hand, has pursued a self-sufficient approach to semiconductor manufacturing, encouraging strategic expansion and accelerations of the country's domestic semiconductor industry. BCG predicts that attempts to address tensions (such as the elimination of tariffs) are unlikely to change the current status quo.[39]

As such, we are likely to see new roads of development and risk management to meet these new approaches. Japan, for example, views the China risk as an opportunity to divest away from China and turn instead toward southeast Asia, favoring companies that are less likely to align with China and jeopardize their corporate futures. Despite the increasing pull toward Southeast Asia, the region is not without its own political risks.

East Asia

The United States literally cannot run without semiconductors made in East Asia, where the majority of chips in the world are produced. At the same time, supply chain disruptions caused by the pandemic over the past two years have made clear just how critical chips are to everyday life in addition to being a vital component for national defense and security.

Looking ahead, Washington has no choice but to invest in its own domestic production capabilities not only to hedge against future disruptions, but also to ensure its own technological integrity. Taiwan alone produces over 90 percent of the world's most advanced semiconductors, and yet the island is in the frontline of facing potential invasion and forced isolation by China. At the same time, Taiwan is vulnerable to earthquakes and other natural disasters, which makes it all the more pressing for Taiwanese chipmakers particularly TSMC to bolster their overseas production bases. Leveraging US commitment to Taiwan beyond defense concerns and into economic security including technology cooperation in chip development and manufacturing will be of strategic interest to both Washington and Taipei.

While Taiwan and South Korea continue to lead the way in developing the most advanced semiconductors, the expectation is that China will catch up sooner or later. Developing mechanisms for technological compatibility and protecting technology as well as information quickly will be paramount for the future of the semiconductor industry. Japan will be a critical partner for the United States in developing a framework for sharing resources and technology with trusted partners in developing a secure and advanced semiconductor industry moving forward.

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Wilson Center Geoeconomics and Indo-Pacific Enterprise

Black Swan 2: Pandemics

As already mentioned, the COVID-19 pandemic, while not exactly a Black Swan event, was not predicted by most decision makers in either government or industry. In terms of the disruption of supply chains, its impact was massive, and we are still dealing with the fallout from the effects of the pandemic on the semiconductor supply chain.

To fully understand the Black Swan events in the context of the semiconductor supply chain, it is imperative to recognize the nuance and specificity in the definition. The COVID-19 pandemic offers a clear example. Unsurprisingly, the term "Black Swan event" gained a resurgence in the vernacular in the spring of 2020 as COVID-19 spread and the world began locking down. For many, this was an "unprecedented" event. However, in the words of Taleb himself with specific reference to the pandemic, the term Black Swan event is not "a cliché for any bad thing that surprises us."[40] Since the 1850s, there have been 16 epidemics that each killed half a million people or more and between the 1957 influenza pandemic and the start of the COVID-19 pandemic in 2020, there has been approximately one pandemic per decade - a trend that experts say is more likely than not to continue.[41]

However, what should now be painfully clear is that we are not particularly good at identifying this kind of risk to the sector, nor have we been effective in responding to the challenge. Ongoing disruptions to manufacturing from zero-COVID policies in China in 2022 have highlighted the enduring impact of public health breakdowns on the globalized manufacturing platform.

Other Black Swans

Conflict and pandemics are front of mind for many policy-makers due to recent events. However, other Black Swan events such as severe drought bringing water shortages, wildfires stemming from those same climatological events, electricity transmission overloads and power outages due to increased demand and severe weather (as seen in Texas in early 2021) or even labor disputes, logistical chokepoints, or political upheaval within key producer countries all feature as potential Black Swan events. In each of these cases, industry and government needs to be prepared, have contingency plans in place, and consider the domino-like effects of an interruption in the semiconductor supply chain.

Gray Rhinos

There are a number of long term challenges of which the semiconductor industry and the US government are aware, and yet in which insufficient progress has been made in recent years. Among these we can identify environmental and human capital challenges, both of which have the potential to constrain growth of semiconductor manufacturing and R&D.

Gray Rhino 1: Water

In 2015, Taiwan was hit by a severe drought, its worst in almost 70 years. In the north of the country, water was cut off to more than a million households two days a week as some dams fell to less than 25% of their capacity.[42] Industrial users also faced restrictions for a limited period. TSMC, the world's largest producer of chips, voluntarily opened up its plants to water inspectors, as the public and government officials raised questions about rationing. In 2021 Taiwan again experienced a historic drought, as monsoon rains failed to arrive. On this occasion, industrial production was affected with temporary factory shutdowns due to water shortages.

Key to this issue are the trade-offs that a nation has to make for water use. During times of abundance, there is little concern as there is plenty of water for all. However, during these times of scarcity, the connection between the semiconductor industry and water came to the fore. Taiwan is home to 11 of the 14 largest semiconductor fabs in the world, with the largest of these facilities consuming as much as 10 million gallons of water a day (the equivalent of 300,000 residential consumers).[42] Although the average semiconductor plant uses between 2-5 million gallons per day, the combined impact during times of drought became a hotly contested issue with political, economic, and ultimately social justice dimensions.[43] During the Taiwan droughts, irrigation for agricultural production was halted to allow for continued use at semiconductor fabs, leading to lost crops and damaged relationships between farmers and the buyers of their harvest. From an investor perspective, the 2021 drought, coming so soon after the 2015 crisis, has been cited as a motivation for some companies to relocate away from Taiwan to the mainland, or to other parts of the world. As droughts become more common in regions where previously there was abundance of water, political figures around the world will increasingly turn to populist policies that may complicate the water needs of private industry. A recent example of this has come in Mexico where President Lopez Obrador speculated that water supply can no longer be guaranteed to private industry in the face of severe drought in the north of the country.

Drought is affecting semiconductor production in Taiwan.

Mexico

In discussions about strengthening America's semiconductor supply chain, Mexico presents unique potential, both in terms of human capital and exports, but domestic politics may present challenges when it comes to bilateral cooperation between the US and Mexico. The Mexican government's investment in initiatives to modernize digital infrastructure and develop STEM educational programs has paid dividends, resulting in significant attention and investments from major companies around the world, particularly in Mexico's three primary tech hubs: Mexico City, Monterrey, and Guadalajara. Each year, over 20% of all graduates from universities in Mexico graduate with degrees in engineering, amounting to over 100,000 graduated engineers per year.[44]

In 2018, Mexico produced nearly 12% of the global semiconductor supply and the country is, worldwide, the 4th largest exporter of cars and the 8th largest producer of electronics – two industries heavily reliant on semiconductors.[45] Though Mexico designs some of the world's most advanced semiconductors, the country is more so known for chips used in electric appliances, ones that generally entail mass production and require less advanced technologies.[46]

Strengthening Mexico's domestic semiconductor production capabilities while simultaneously growing collaborative production within North America is of key interest to Mexico to strengthen the resiliency of the country's electronics and automotive manufacturing industries, the latter of which comprised 20% of Mexico's GDP in 2017.[47]

Despite discussions of the complexity of the semiconductor supply chain, there are those, such as Santiago Cardona (IT Vice President of CANIETI and CEO of Intel Mexico), who believe that Mexico has the tools to be self-sufficient in the industry, thanks to Guadalajara's design and programming centers and Northern Mexico's manufacturers. Officials in the Mexican government, such as Tatiana Clouthier (Mexico's Minister of Economy), have reiterated their commitment to co-producing semiconductors alongside the US. As both the importance and complexity of semiconductor supply chains becomes increasingly apparent, Mexico has a clear opportunity to play a crucial role in the sector, however, domestic challenges, such as economic nationalism and republican austerity, as well as long-term challenges of clean renewable energy and reliable water supply remain significant obstacles to moving the sector forward in Mexico.

Alexandra Helfgott
Wilson Center Consultant

The global semiconductor crunch during 2020-22 has been a major driver around the world for companies and governments to look at expanding production and re- or near-shoring closer to the US. In doing so, water needs have been a factor in the decision of where to build new capacity, though it is important to note that, "…chip-fabrication plants are similar to indoor swimming pools—'you need a lot to fill it, but you don't have to add much to keep it going.'"[49] But the industry has increasingly been taking measures to reduce its water footprint, such as Intel's substantial investments in water conservation and restoration projects.[50] The 2015 and 2021 Taiwan droughts brought closer scrutiny of water use in fabs, both by governments and the industry itself, with companies increasingly turning to water recycling and water reduction technologies to reduce their drain on public resources. Intel has even set an ambitious goal of by 2030 in net positive water usage (combination of water re-use plus restoration of watersheds).[51]

Gray Rhino 2: Energy

As with water, the semiconductor industry is highly energy intensive. According to a 2013 McKinsey report, a typical fab's power use is equivalent to that of 50,000 homes and certain "megafabs" require more electricity than auto plants and refineries.[52] This intense energy usage accounts for between five and 30% of fab operating costs.[53] In an era of volatile electricity prices due to geopolitical tensions and energy supply concerns, this ratio becomes a factor that can deeply impact the competitiveness and final pricing of chips.

In the years since that report was published, it is true that the industry has made impressive strides in improving energy efficiency. The use of metering, which raises the visibility of energy consumption within the fab, and technologies such as new cooling systems using air rather than water, automatic transfer switches, energy efficient uninterruptible power supplies, and optimized electric distribution architectures, have been successful in reducing energy intensity by between 20-30%. However, with demand for semiconductors growing so rapidly, overall energy use is growing too.

Investment decisions in the semiconductor supply chain, of course, are driven by the combination of multiple factors. However, the cost, availability and, increasingly, carbon intensity of the energy supply have become critical variables in determining where semiconductor companies choose to build new capacity. Some major players in the sector have targeted net zero emissions by 2040, a goal that will be a significant factor in future investment location decisions.[54] Offering access to reasonably priced, climate friendly, and reliable energy sources greatly increases the attractiveness of a potential fab location, and many semiconductor firms will no longer consider jurisdictions in which these three variables cannot be guaranteed.[55]

Gray Rhino 3: Human Capital

A 2017 study from Deloitte and SEMI found that 77% of survey respondents believed that the semiconductor industry was experiencing a severe talent shortage, one only likely to worsen in the coming years.[56] Unsurprisingly, the semiconductor industry relies heavily on STEM graduates, but the report found that there is a widespread struggle to attract new talent, particularly engineers. The report partially attributes these hiring challenges to issues of branding and perception, especially among younger hires, and 59% of the survey's respondents shared that the semiconductor career path is not as attractive as that of other technology-related industries.[57] In addition to the poor brand perception, the Wilson Center's working group found that there is a critical lack of necessary resources to offer training and support, especially for large, globalized companies and argued the substantial need for workforce development, across the entire ecosystem – from test engineers, firm and software developers and operators, designers, and technicians – and across all levels of education. Immigrants play a crucial role in the US semiconductor industry - across all occupations, from electrical, electronic, and electro assemblers to semiconductor processing technicians and industrial engineers.[58] As the domestic US manufacturing labor force continues to face challenges in terms of recruitment and retention, highly skilled immigrant labor could play a key role in filling the talent gap. One suggestion entails a strategic combination of skills retraining programs and the expansion of the H2-B visa program to permit temporary, nonagricultural workers into the US to address labor shortages.[59]

The semiconductor industry is inherently human capital intensive, requiring specialized knowledge and skills across the supply chain – from R&D and manufacturing to packaging and installation in final goods. SIA and Oxford Economics' 2021 report, "Chipping In: the positive impact of the semiconductor industry on the American workforce and how federal industry incentives will increase domestic jobs" found that in the US, through direct, indirect, and induced impact, the semiconductor industry employed 1.85 million people and contributed (GVA) $246.4 billion in 2020 alone (SIA). The vast majority of these jobs pertain to manufacturing and professional and business services. Over a quarter of a million people in the US work directly in the semiconductor industry in design, manufacturing, testing, and R&D. Of note, the semiconductor industry ranked in the 85th percentile for its jobs multiplier score, meaning that "for every direct job in the semiconductor industry, an additional 5.7 jobs are supported in other industries."[60] In 2019, the semiconductor industry supported over 25 million jobs in the US across various industries including, but not limited to: printing, telecommunications carriers, custom computer and programming services, bottled and canned soft drinks packaging, plastics packaging, and electromedical detection and navigation instruments manufacturing.[61]

Like many other elements of the semiconductor supply chain, the human capital component is significantly time intensive, with timelines that are bound by the limits of knowledge and skill acquisition. Within the semiconductor industry, there is occupational diversity, with needs for employees to fulfill roles in management, sales, transportation, and business operations. However, architecture, engineering and production make up 23.9% and 38.6%, respectively, of total occupational share in domestic semiconductor production.[62] The average age of employees in the semiconductor industry is between 35 and 49 years old, as compared to all other industries in the US for which the age range averages between 16 and 34 years old, indicating a "graying workforce."[63] This difference highlights the "length of tenure within the industry as well as industry knowledge."[64] The report highlights the uniqueness of the semiconductor industry in that it offers opportunities for a range of skills and educational levels as "…workers consistently earn more than the US average at all education attainment levels.[65]" For example, 35% of semiconductor employees do not have a college degree.[66]

The Talent Challenge

Talent has become a major concern for the industry. In a 2021 survey of semiconductor industry leaders by KPMG, 30% named talent as one of the top 3 risks threatening their ability to grow over the next three years. Salary statistics also point to talent supply constraints; wages in the U.S. semiconductor industry have been growing an average of 4.4% since 2001, significantly faster than the growth in wages for the economy as a whole. Talent shortages have the potential to significantly reduce the industry's long-term ability to maintain its rapid pace of innovation. The industry workforce is aging, with a significant number of current employees in technical positions likely to retire in the next 10-15 years. Furthermore, the industry needs to attract talent with different skill sets, particularly in software development and artificial intelligence. Most of the needed talent for the semiconductor industry will come from university undergraduate and graduate programs. Obviously, the more sophisticated roles will be filled by graduate students, who are conducting research with funding grants from the government, research consortia, and directly from industry.

John Fowler
Arizona State University

Diversity is also a challenge in the industry. According to Pew Research, "the growth in STEM degree recipients has far outpaced that for all degrees," with the number of STEM degrees growing by 62%, as compared to 20% growth for all other degrees from 2010-2018.[67] Though women make up nearly half of the US workforce, they only constituted 29% of the STEM workforce in 2017, though this is up from 22% in 1995.[68] Of note, in 2017, women earned 50% of all STEM degrees awarded.[69] In terms of racial and ethnic diversity in STEM, Black people make up nearly 12% of the US adult population, but only account for 7% of STEM highest degree holders and in 2017, only 9% of all STEM degree recipients were Black.[70] Hispanic and Latino people make up 16% of the US adult population, but only 9% of STEM degree holders.[71] In 2017, however, Hispanic and Latino people were awarded 15% of STEM degrees, indicating closer achievement of parity with overall population.[72] Though only 6% of the US resident population over the age of 21 consists of Asian people, this group holds 16% of highest STEM degrees earned and consists of 20% of all STEM workers in the US.[73] However, Asian women are underrepresented in the industry, with only 5% working in managerial roles.[74]

The current human capital challenges facing the semiconductor supply chain are expected not only to persist, but in fact, worsen over the coming years and decades as the demand for chips continues to skyrocket, outpacing previous rates of production. The Semiconductor Research Corporation's Decadal Plan for Semiconductors lays out five "seismic shifts" that will "define" the future of semiconductors, including profound breakthroughs in technology that will require a shift from analog hardware to machine-based learning technology and require substantial financial investment; the demand for new memory and storage solutions; the development of leading-edge research to address the disparity between communication capacity and data-generation rates; the need for research and hardware to address security challenges associated with AI and other advanced, interconnected technologies; and opportunities to improve energy efficiency through "new computing paradigms."[75] Throughout all of these shifts, human capital will play a significant role and a fierce competition for talent is likely to ensue, with some experts predicting that US talent will be recruited internationally.

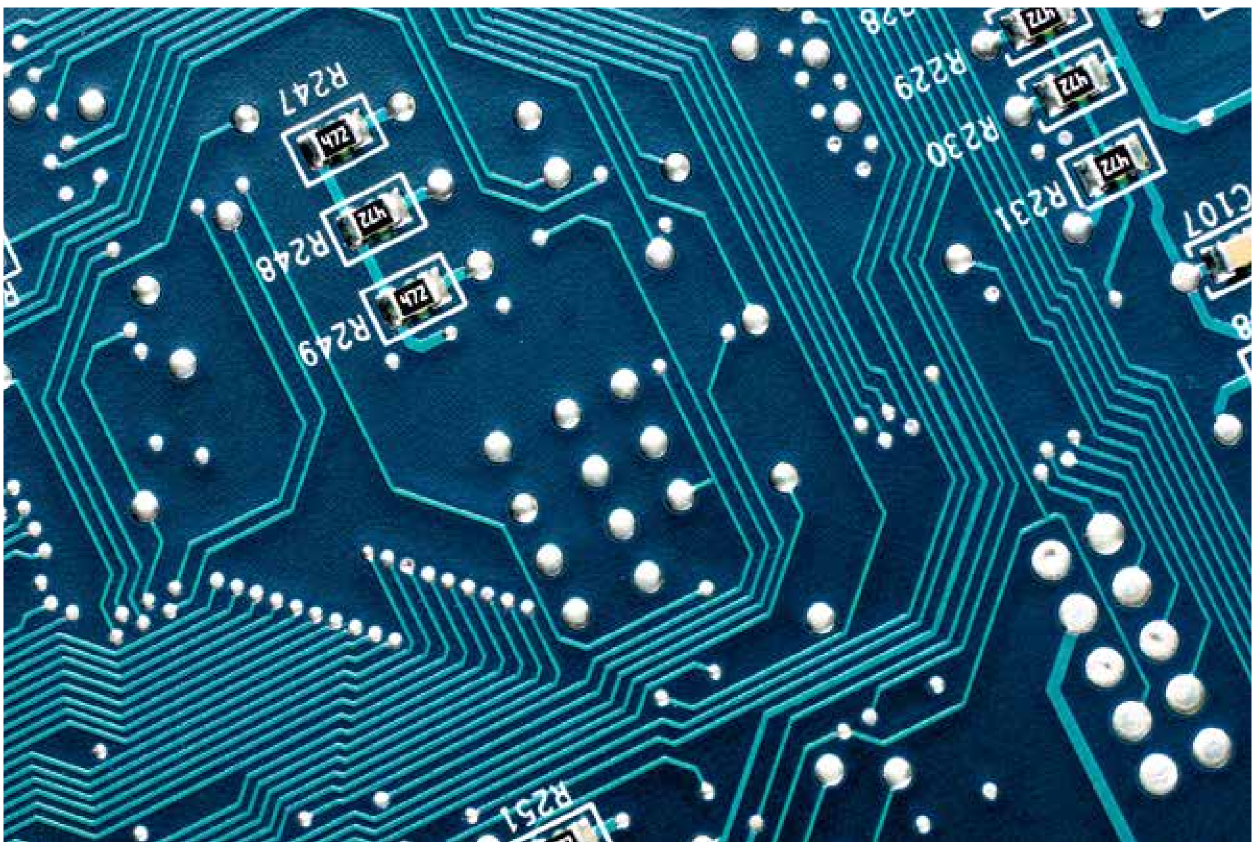
Recommendations

In its 100 Day Review of the semiconductor supply chain, the Biden administration laid out a series of recommendations for the sector:

- Promote investment, transparency and collaboration, in partnership with industry, to address the current shortage
- Fully fund the CHIPS for America provisions to promote long-term US leadership
- Strengthen the domestic semiconductor manufacturing ecosystem
- Support SMEs and disadvantaged firms along the supply chain to enhance innovation
- Build a talent pipeline
- Work with allies and partners to build resilience
- Protect the US technological advantage

The CHIPS and Science Act of 2022 commits $280 billion in federal funding to strengthen the US semiconductor supply chain, specifically in R&D and manufacturing, and expand R&D for advanced technologies such as quantum computing, AI, and advanced energy.[76] The $170 billion invested in science has enormous potential to improve R&D and STEM education in the US and it is these R&D provisions in the CHIPS and Science Act that significantly distinguish this legislation from the initial CHIPS Act. The legislation designates a total of $54.2 billion for domestic semiconductor research, development, manufacturing, and workforce development.[77] Of this, $50 billion has been appropriated to the CHIPS for America Fund, $39 billion of which has been allocated for the Department of Commerce Manufacturing Incentives, intended to fund the building, updating, and expansion of domestic facilities and equipment for R&D, advanced packaging, assembly, fabrication, and testing.[78] The additional $11 billion is designated for R&D and will be administered by Commerce and includes various programs such as, the National Semiconductor Technology Testing Center, the National Advanced Packaging Manufacturing Program, the Manufacturing USA Semiconductor Institute, and the Microelectronics Metrology R&D. The legislation allocates $200 million for the CHIPS for America Workforce and Education fund to further develop the domestic semiconductor workforce. The CHIPS for America Defense Fund received an allocation of $2 billion and will be administered by DoD for the Microelectronic Commons and further semiconductor workforce training. The CHIPS for America International Technology Security and Innovation Fund received a $500 million allocation in support of international information security and supply chain activities which will be coordinated by State, USAID, Export-Import Bank, and International Development Finance Corporation. The legislation also includes $1.5 billion for the Public Wireless Supply Chain Innovation Fund to strengthen US leadership in wireless technologies.

The CHIPS and Science Act of 2022 also includes guardrails to limit funding recipients from building facilities in China and other countries of concern. CHIPS Act funding recipients are required to demonstrate community investments, with a particular emphasis on small businesses and disadvantaged communities, and for facility construction jobs, funding recipients must follow the Davis-Bacon prevailing wage rate.[79] The legislation also stipulates a 25% tax credit for "capital expenses for manufacturing of semiconductors and related equipment."[80] The CHIPS and Science Act of 2022 allocates nearly $170 billion for R&D throughout the next five years across key entities such as the National Science Foundation, Department of Commerce, the National Institute of Standards and Technology, and the Department of Energy. The Act's emphasis on R&D is hugely significant and represents "the largest five-year investment in public R&D in the nation's history."[81] The legislation also stipulates a total $82.5 billion increase over baseline.



CHIPS and Science Act of 2022[82]

Division A, CHIPS and ORAN (also known as Public Wireless Supply Chain Innovation), Appropriations Summary:		
CHIPS for America	**$50 billion**	
Department of Commerce (DOC) Manufacturing Incentives	$39 billion	Funding to build and modernize equipment and facilities for domestic semiconductor fabrication, assembly, advanced packaging, and R&D. $2 billion specifically designated for mature semiconductors and up to $6 billion for direct loans and loan guarantees.
DOC R&D	$11 billion	Funding will go toward DOC's National Semiconductor Technology Center, National Advanced Packaging Manufacturing Program, Manufacturing USA Semiconductor Institute, and Microelectronics Metrology R&D.
CHIPS for America Workforce and Education	**$200 million**	Funding to develop US semiconductor workforce via activities of the National Science Foundation.
CHIPS for America Defense Fund	**$2 billion**	Funding for semiconductor workforce training and implementation of the Microelectronics Commons, a national network for the development of lab-to-fab transition of semiconductor technologies, to be led by the Department of Defense.
CHIPS for America International Technology Security and Innovation Fund	**$500 million**	Funding to support international information security and supply chain activities. State will lead the coordination in collaboration with USAID, Export-Import Bank, and International Development Finance Corporation
Public Wireless Supply Chain Innovation Fund	**$1.5 billion**	Funding to strengthen US leadership in open-architecture and wireless technologies.
TOTAL:	**$54.2 billion**	

Division B, Research & Innovation, Funding Authorization Summary:		
Programs:	**Five-Year Authorization:**	**Increase Over Baseline:**
National Science Foundation (NSF)	**$81 billion**	**$36 billion**
NSF Tech Directorate	$20 billion	$20 billion
NSF Core Activities	$61 billion	$16 billion
Department of Commerce (DOC)	**$11 billion**	**$11 billion**
DOC Regional Technology Hubs	$10 billion	$10 billion
DOC RECOMPETE Pilot	$1 billion	$1 billion
National Institute of Standards and Technology (NIST)	**$10 billion**	**$5 billion**
NIST Research	$6.9 billion	$2.8 billion
Manufacturing USA	$829 million	$744 million
Manufacturing Extension Partnership	$2.3 billion	$1.5 billion
Department of Energy (DOE)	**$67.9 billion**	**$30.5 billion**
DOE Office of Science	$50.3 billion	$12.9 billion
Additional DOE Science and Innovation	$17.6 billion	$17.6 billion
TOTAL:	**$169.9 billion**	**$82.5 billion**

The CHIPS and Science Act of 2022, although a significant step in the right direction for the US semiconductor industry, cannot be seen as a “silver bullet” for the nation’s semiconductor supply chain challenges. The promotion of “investment, transparency, and collaboration” in the national semiconductor industry is vital, of course, not only to address the short-term deficits in the supply of semiconductors, but to address the long-term challenges of re-shoring production, building a talent base, addressing environmental, energy and water issues, and meeting the China challenge.

The protection of the US semiconductor industry refers to national security-related actions to protect US technological leadership, like export controls, the Committee on Foreign Investment in the United States, and other supply chain restrictions. “Promote and protect” must become a motto for the US as it addresses the semiconductor supply chain, but the term does not fully convey the need for a sustained strategic approach to building resilience in the sector. This means continuing to work with the industry to address evolving issues and overcoming vulnerabilities.

Industry Responses to Supply Chain Breakdown

Given the pervasiveness of semiconductors in modern life, to what extent should the level of analysis and focus be on scoping resiliency problems? Some members of the working group suggested an emphasis on planning for and ensuring particular customers, rather than focusing on covering their entire customer base. Other members suggested that fostering resilience in the semiconductor supply chain should be a broader conversation focused at the societal level because issues of the semiconductor supply chain have such a wide scope, as exemplified by the current chip shortages and their ripple effect. At what point in the crisis should the aperture be dialed back to understand the totality of the BSE/crisis' impact? And one of the most difficult questions posed by the working group - in the wake of a BSE, who is responsible? What does taking responsibility look like?

While every organization and government will likely answer these questions differently, historical precedent may offer some key answers. At the industry level, for example, the Semiconductor Industry Association (SIA) has been able to respond successfully to unanticipated semiconductor-related changes. SIA's industry-only communication mechanism has proven successful in times of crisis, such as in the 1990s when chips became rad-hard and faced export control. When the US experienced a shortage of helium, SIA worked collectively to get US-based fabs access to critical reserves of helium. At the international level, there is the World Semiconductor Council which was formed in 1996 and includes the SIA of the United States, Korea, Japan, Europe, China, and Taiwan. The Council's primary focus is "promot[ing] international cooperation in the semiconductor sector in order to facilitate the healthy growth of the industry from a long-term, global perspective" across four key issue areas: environment, safety, and health; intellectual property; free and open markets; and monitoring market size and growth trends. During the COVID-19 pandemic, for example, the Council shared cross-country intelligence and worked to do joint advocacy to establish semiconductor production as a critical industry, meaning plants could stay open during government-mandated stay-at-home orders. Despite its broad nature, the Council has been less successful when it comes to market dynamics, particularly in terms of issues of supply and demand beyond striving to have supply match demand.

A Role for Government AND Industry

Prior crises have illustrated a general response pattern: the private sector and corporate world reacting first and governments following. In part, this is because industry is most and earliest affected by the problem and in part because the US government, even when it understands the problem and wants to move fast, is constrained by logistical issues (e.g., the size of government bureaucracy and the process of coordinating across the interagency) and legal issues (e.g., ensuring any rule that comes out to solve the problem complies with the Administrative Procedure Act, which requires a sufficient record to show the government considered the reasonable options).

However, given the complexity of the semiconductor supply chain and the existence of both Black Swan and Gray Rhino events, including geopolitical, logistical, energy, water and human capital considerations, it is clear that the federal government must play an increasingly prominent and hands-on role in the semiconductor industry. The delicate balance is that, although the government is able to wave the "big wand," it significantly benefits from specific guidance and direction from industry. Some working group members argued that the role of the government in the semiconductor industry should be to incentivize decisions that wouldn't otherwise be taken, whereas others felt that collaboration with government should be limited as having one entity take the lead can create a single point of failure. Market dynamics (such as the current shortage combined with the high level of demand) are where limitations emerge. In some cases, there's a government echo effect and a tendency for governments to be nationalistic which leads to increased uncertainty in the marketplace and perhaps at the most inopportune time - in moments of crisis.

Given the complexity of the semiconductor supply chain and the existence of both Black Swan and Gray Rhino events, including geopolitical, logistical, energy, water and human capital considerations, it is clear that the federal government must play an increasingly prominent and hands-on role in the semiconductor industry.

There are considerable knowledge resources in both government and industry that can be combined effectively in crises. For example, the US government has broad technological knowledge in the semiconductor industry, ranging from commercial inputs and market effects, to military uses, and other civilian uses. Perhaps most importantly, the government has the ability to view the semiconductor industry in the context of national competitiveness and national security.

Across industries and disciplines, various scholars and practitioners have developed suggestions and guidelines for preparing for and managing unpredictable exogenous shocks. Keith Dodson and Richard Westney's 2014 piece, "Predictable Projects in a World of Black Swans," offers a five-step framework for stakeholders to deal with Black Swan events.[83] These steps include:

- hunting the Black Swan (in industry language, risk framing);
- caging it (developing risk strategies - both to mitigate impact and finance risk coverage);
- understanding it (risk assessment of "tactical and strategic risks" and their associated capital costs);
- feeding it (risk brokering); and
- taming it (risk validation via the management of "known unknowns" and active situational assessment for Black Swan events).

When looking at disruptions to the semiconductor supply chain, be it Black Swan events or otherwise, it is imperative to recognize the downstream impact, particularly on end-users. Too often, contingency planning focuses on triaging immediate circumstances, with both intentional and unintentional disregard for the downstream impact. One disruption can have a calamitous cascading effect across the supply chain and further downstream with impact felt by average consumers, as has been the case with rising car prices. High car prices (primarily driven by the shortage) were responsible for a third of inflation in 2021-22.[84] Not only do semiconductor companies have a responsibility to develop resilience and agility to avert catastrophic consequences of exogenous shocks, but downstream/end-use consumers also maintain a responsibility to develop their own contingency plans. Participants in all industries that use chips need to play a partnership role with the semiconductor industry to ensure their procurement actions (sole sourcing, just-in-time inventory/parts management, demand planning, lead-time forecasting) when aggregated with the actions of others does not put broader constituencies at risk.

A word here about timing. On average it takes three years to build a new fab.[85] That means that the earliest a new fab could start producing semiconductors would be two years after the relevant permits have been secured from national, state, and local authorities. One working group member confessed their company's own struggles to get policymakers to understand the lengthy semiconductor fab construction and production timeline and shared the common misunderstanding of what it takes for a company to move and/or change manufacturers. Bringing a fab online takes much longer than end-use product manufacturers and consumers are likely to realize. In addition to ramping up efforts to make the complexity of the supply chain more widely recognized, particularly among industries reliant on semiconductors, the working group recognized the necessity of conveying the domino effect of the semiconductor supply chain, specifically in terms of how these changes can significantly impact supply and demand further downstream for industries reliant on semiconductors.

Preparing for Volatility: Geopolitics and Black Swan Events

We cannot predict exactly what volatility will impact the future of the semiconductor industry, but there are steps that we can take to make the supply chain more resilient. Policy options to achieve this goal include the diversification of the geographic footprint of the global supply chain, an understanding of the minimum fab capacity required for national security reasons, and strategic thinking about the need for diversification in light of geopolitical crises or other Black Swan events.

First, there is an urgent need to reshore fab capacity here to the United States, as well as to put them into neighboring and friendly countries.

There is already encouraging movement in this regard, with major companies recently announcing new investments. However, to build on this progress and to accelerate the rate of investment and growth in national capacity and industry ecosystems, the US Congress should take the necessary actions to address the challenges facing investors. Leading up to the successful passage of the Act, several semiconductor companies indicated that they would invest in new capacity in other countries if the CHIPS funding was not forthcoming. In the future, this must be a consideration for Congress and the Administration as they try to attract more investment to the US.[86]

Because the semiconductor supply chain is so fundamentally interconnected, discussions of the supply chain, strengthening resilience, and fostering agility cannot be siloed conversations. The notion that any one country can indigenize the semiconductor supply chain is not realistic. The current challenges facing the semiconductor supply chain are likely to evolve in the coming decades but will be built upon the challenges the industry is currently facing. The US and its allies must engage with China in order to effectively develop a full scope understanding of the global semiconductor supply chain and its implications for US industry and manufacturing. Certainly, caution must be maintained, but Chinese strength in the industry is unlikely to shrink and the United States cannot have conversations about strengthening its semiconductor supply chain without thinking about the bigger picture, which includes China.

To protect the US lead in advanced semiconductor R&D, government measures should seek to lower the costs of production in the US, and to fund future research in the STEM disciplines and specifically on semiconductors (without industry

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reducing its own commitment to such funding). The US must also actively promote reshoring and ally-shoring strategies to strengthen the semiconductor supply chain. When it comes to the potential for an interruption of Taiwanese chip production caused by Chinese actions against the island, for example, there is no doubt that, given the current state of the supply chain, the results would be disastrous. The diversification of the supply chain through reshoring and ally-shoring of the industry will take time, but in the short and medium term it will be difficult or impossible to shift the structure of the global industry to eliminate the risk.

Mitigating the impact of such exogenous shocks must therefore be a priority. The Biden administration has noted that the government can play a positive role in encouraging "investment, transparency, and collaboration" between government and industry. This must be done in a collaborative way, working with industry to avoid policy implementation that backfires. This collaboration should focus on two themes: the continuous assessment of signals of an impending crisis; and the creation of a group of "first responders" that take proactive responsibility and coordinate activity among semiconductor companies, downstream industry, and government. It's also vital for companies that are reliant upon semiconductors to lead their own stress tests to understand the immediate and long-term impacts of disruptions higher in the supply chain on their own production. Transparency is a fundamental element in ensuring preparation, agility, and responsiveness, but it is important to note that transparency comes with its own challenges. Publicly discussing choke points and vulnerabilities of the semiconductor supply chain presents a real challenge and both industry and government will need to strike a balance between promoting transparency without compromising security.

Perhaps just as important as the development and implementation of supply-chain circuit breakers and protocols is the need for a sustainable and enduring approach of management of and preparation for "high-consequence, low-probability events." The COVID-19 pandemic offers a clear and tangible example of resilience (or lack thereof) in terms of emergency readiness, preparation and responsiveness. Scarcity is always a factor, but one that becomes even more pronounced during a prolonged crisis. The industry default is to emphasize capital efficiency through the elimination of redundancy which directly harms contingency planning and preparation for Black Swan events as it leaves little to no room for error. As an article in the Harvard Business Review puts it, "Overspecialization hampers companies' evolution," posing a direct threat to crisis responsiveness.[87] There is a clear need for the development of a strategic and comprehensive approach to develop, foster, and sustain resilient infrastructure that can quickly and appropriately react to exogenous shocks in the semiconductor supply chain.

We don't need to manufacture advanced nodes everywhere but have sufficient diversity around the globe so we are not subject to chaotic consequences if any one location has a Black Swan event. No one country can be self sufficient (SIA/BCG study data captures the unacceptable cost of that) so we need diversity with some mutual dependence (e.g. more capacity in US, Europe and other countries to complement what has been successfully developed in Asia today but not to create just more competing capacity as an end goal in itself)[88]. The industry should decide where to best locate fabs of different technology nodes that can be the most economically productive in their locations depending on customer demands, input costs, availability of talent and the USG should create incentives to level the playing field as much as possible so that there are choices.

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While media coverage of the current chip shortage often frames the issue as "unprecedented," the truth is that the semiconductor industry is cyclical. The internet bubble of 2000, the financial crisis of 2008 and the start of the Covid pandemic in 2020 all resulted in a precipitous decline in demand for semiconductors, followed by an incremental rebound, identified by Accenture as a six-part cycle: "new fabs are built, over capacity happens, pricing drops, demand increases, capacity tightens, pricing increases."[89]

As we consider potential volatility not only in terms of supply, but also of demand for semiconductors, government and industry decision-makers will need to address peaks and troughs in the demand cycle and find ways to keep supply steady. More industries than ever before are interacting with the semiconductor supply chain, and it is clear that we need to improve our understanding of the demand process, reserving capacity, and canceling capacity within the industry. The industry itself must recognize its responsibility not to create monopolies, nor to generate over-dependencies on one country, or company. The existence of sole suppliers and minimal built-in redundancy is efficient, but overly risky.

Toyota's approach to addressing ebbs and flows of demand has traditionally been through inventory accumulation. Following the 2011 Fukushima nuclear disaster, the company decided to hold months' worth of inventory in preparation for future exogenous shocks. In this case, the cost of holding and storing the excess inventory paid off a decade later as Toyota was able to continue producing, despite shortages in supply and increasing demand across the market. Though there are significant costs to this approach, dominating market supply by being able to supply products when other companies cannot be considered is an advantageous strategy.

The broader auto industry, however, has adopted a different strategy when it comes to supply chain disruptions. In fact, the auto industry has been widely acknowledged as driving its own shortage by its just-in-time delivery model. During the COVID-19 pandemic, for example, demand in the auto industry decreased substantially and automakers sought to limit inventory of parts in order to reduce costs.[90] As a result, semiconductor companies pivoted from mature auto chips to other chips for computers, tablets, and the like.[91]

Preparing for the Gray Rhino: Energy, Water and Human Capital

While future Black Swan events are almost certain to impact the global semiconductor supply chain, their exact nature is unknown. There are, however, Gray Rhinos on the horizon whose significant impacts are already becoming increasingly visible. The Working Group discussed various Gray Rhino challenges, but it quickly became clear that energy, water, and human capital are the most significant on-the-horizon challenges for the semiconductor industry.

The semiconductor industry is already on a path to increasing the use of clean energy and reducing energy intensity. However, the argument for further boosting renewables as a source of energy for the industry became even clearer in 2022 with the energy price shock brought on by the Russian invasion of Ukraine. With energy prices rising rapidly, firms that have invested in renewable energy sources have been able to keep energy costs steady. That certainty will become more and more important in determining investment decisions.

Although there is no specific standard for emissions reductions from the semiconductor industry, each of the major players are now working toward a common goal of net zero. It is interesting to note that the pressure to reduce emissions has come, not from governments who have been more concerned with the question of strengthening the supply chain, but rather from investors and shareholders who are increasingly concerned over climate change and therefore building it into their investment decisions. Consumer and civil society groups have also been significant players in the broader effort to improve ESG standards. From the industry perspective, reducing emissions, using renewable energy sources and reducing energy intensity provide a win-win proposition, diminishing costs, increasing certainty and improving ESG compliance.

The availability of water, both in terms of quantity and quality, remains an issue impacting the location of future fabs, particularly as drought becomes more common in areas where there was previously abundance of supply. With shifts in the distribution of water resources due to climate change, governments and industry must look to investing more heavily in modern water infrastructure to store rainfall, reduce evaporation from reservoirs, irrigation canals and lakes, and look to innovative approaches to reduce overall water waste across the economy. The availability of clean water is a critical factor in determining the siting of future fab capacity. Circular economy approaches that allow for extensive water recycling, and even providing surplus clean water to local communities, are becoming increasingly common in fabs. Reducing water intensity in the production process also helps to reduce energy intensity (due to the energy cost of pumping water) and will certainly improve relations with local stakeholders.

In terms of human capital, the working group advised that plans to increase production capacity through the creation of fabs be paired with substantive plans and legislation to fund training, educational, and workforce development programs – both for new hires and for career path/lifelong learners. The government and the private sector must work in tandem to provide opportunities to strengthen recruitment and retention practices, enhance workforce development, and foster the human capital growth and development necessary to sustain growing demand for semiconductors. Through the federal investment to be allocated through the CHIPS and Science Act, the SIA predicts the creation of nearly 200,000 jobs per year and a total GDP contribution of $147.7 billion from 2021 until 2026.[92] This investment will only further increase demand for talent within the semiconductor industry and as such, it will be essential for government and industry to collaborate to attract, hire, and retain workers across the various occupations that are essential to the semiconductor industry.

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One of the biggest takeaways on the topic of human capital from the working group is the necessity of partnership between industry and academia; the two should work together to leverage strengths to address weaknesses in the semiconductor industry. Across the semiconductor industry, there is the challenge of recruiting interested and qualified candidates into the pipeline and then actually retaining them. While this is a challenge across the board, it is especially pronounced among historically underrepresented groups. In terms of racial and ethnic diversity, the US semiconductor industry "employs a greater share of non-white workers when compared to the manufacturing sector and all other industries in the US."[93] Asian people far outnumber Black and Hispanic people in the US semiconductor industry, accounting for 28% of the entire workforce, whereas Black and Hispanic people account for 4% and 13% respectively.[94] However, it is important to note that recruitment is only part of the problem; the industry faces significant issues of retention. For example, executive-level respondents in the Deloitte/SEMI survey said that 60% of their employees leave their jobs within three to five years of beginning them.[95] This is partially attributable to high rates of burnout, headhunting by other firms (across similar and different industries), and basic difficulties in providing and ensuring long-term career paths.

Additionally, there needs to be an intentional retraining piece and a cultural shift in corporations involved in the semiconductor industry. A portion of this retraining directly involves universities and community colleges and their key role in providing candidates for the hiring pipeline. In fact, one working group member suggested that US community colleges offer specific degree and certification programs around what skills and knowledge it takes to operate these high-tech machines and tools. If the workforce is not receiving the appropriate education and training, companies won't have a pool of candidates from which to hire. Moreover, there exists the opportunity for the industry to make employees feel engaged, involved, and appreciated at work, while also providing ample growth prospects and career development opportunities – all of which will only strengthen the US semiconductor industry.

As the topic of semiconductors further enters the awareness of average consumers, the private sector is uniquely positioned to make a substantial impact on the industry's human capital and workforce development and should capitalize on the opportunity ahead. For example, the semiconductor industry needs to broadly convey their profound impact– not just at the deeply technical level, but at the most basic level, making communities aware of just how prevalent and necessary chips are in daily life – from planes and cars to electric toothbrushes and cellphones – in an effort to attract and recruit new talent to the industry, across all sectors.

Concluding Thoughts

Semiconductors have become the keystone for modern industries and the growth in demand is significant. The intricate and highly specific nature of the supply chain, including R&D, manufacturing, and packaging, has been made possible by a globalized production system with an international division of labor. That globalized system, long taken for granted by industry and government alike, is now being challenged by regional concentration, ever-changing geopolitical dynamics and competition, and exogenous threats, both predictable and not, that have exposed vulnerabilities in the supply chain. Of particular relevance is the growing importance of geopolitics and competition, exacerbated by heightened tensions and the threat of a highly disruptive conflict in the East Asian theater.

Current challenges facing the semiconductor supply chain were decades in the making and, as such, cannot be expected to be resolved overnight. Time is short to take action and it is our hope that this report motivates further and sustained attention, conversation, and analysis of the multifaceted issues facing the semiconductor supply chain and encourages concerted collaboration across government, industry, and academia to address what is certain to be one of the most relevant and pressing issues of the first half of the 21st century. The CHIPS and Science Act is a strong start but will not completely solve the issue and additional targeted policy action will need to be taken in the future. This is not "one and done." Drawing on the collective knowledge and expertise of members from across government, private sector, and academia, we argue that a strategic approach, encouraging public private consultation and collaboration, is essential to addressing ongoing vulnerabilities and risks in the supply chain.

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