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ABSTRACT: The United States government must take action now to secure the supply chain for semiconductors, promote economic growth, and sustain the United States' technological competitive advantage for the future. China's state-led efforts to develop its domestic semiconductor industry are unprecedented in scope and scale and represent a direct threat to the United States' economic and national security interests. The Department of Defense (DoD) requires secure access to semiconductors to support both cutting-edge and legacy capabilities.

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List of Acronyms and Key Terms

AI	Artificial Intelligence
ATP	Assembly, Testing, and Packaging
CFIUS	Committee on Foreign Investment in the United States
CHIPS	Creating Helpful Incentives to Produce Semiconductors
DARPA	Defense Advanced Research Project Agency
DMEA	Defense Micro Electronics Activity
EDA	Electronic Design Automation
EUV	Extreme Ultraviolet
fab	Fabrication facility
IC	Integrated Circuit
IDM	Integrated Device Manufacturer
IoT	Internet of Things
IP	Intellectual Property
NDAA	National Defense Authorization Act
NSTC	National Semiconductor Technology Center
OEM	Original Equipment Manufacturer
OSAT	Outsourced Assembly and Test
PC	Personal Computer
PV	Photovoltaic
R&D	Research and Development
SoC	System on a Chip
SOTA	State of the Art
SOTP	State of the Practice
SIA	Semiconductor Industry Association
STEM	Science, Technology, Engineering, and Math
TSMC	Taiwan Semiconductor Manufacturing Corporation

Executive Summary

Semiconductors are ubiquitous across the electronics industry and represent the keystone of the digital age. The global market for semiconductors was valued at $600 billion in 2021 and is expected to grow to $1 trillion by 2030. The United States owns 47% of the semiconductor market but is lagging in critical areas and its lead is deteriorating. The U.S. has passively observed the migration of semiconductor manufacturing capacity to China and other parts of Asia over the past 30 years. Government investment into R&D is not keeping pace with other nations, creating a risk to innovation, the lifeblood of the United States' historical competitive edge. America can remain complacent no longer. The U.S. and its allies must remain in the lead of the semiconductor industry to protect national security, ensure economic prosperity, and maintain rules-based world order.

Semiconductors present a wicked problem for the United States leadership. The globally integrated semiconductor ecosystem has created economic efficiency but has become a critical vulnerability and threat to national security. Dependence on semiconductor chips sourced from competitors, such as China, has the potential for counterfeits and compromise of critical systems such as military weapons and critical infrastructure. Decoupling from nations whose values do not align with the U.S. remains challenging due to market forces or a lack of viable alternatives.

The COVID-19 pandemic exposed vulnerabilities to the global supply chain and created a shortage of semiconductor chips across other industries. Governments and industries are working to expand capacity to meet the growing demand for chips, but geopolitical dynamics and other natural disasters continue to disrupt supply chains. Three interrelated dynamics drive the inability to establish a reliable, secure supply of semiconductors: first, the rising dominance of China in the semiconductor ecosystem and its geopolitical assertiveness, second, the geographic dispersion of the value chain throughout the global ecosystem, and third, the shallow value chain.

This paper uses Porter's Diamond Model to analyze U.S. national competitiveness in the semiconductor market. The U.S. semiconductor ecosystem has critical shortfalls in all four model points (firm strategy, structure, and rivalry; related supporting industries; demand conditions; and factor conditions). Major issues fall into the categories of human resourcing shortfalls, deficiencies in R&D to spur innovation, and enforcement of international trade policies.

Deterioration of the U.S. semiconductor competitiveness has garnered enough attention for the government to respond. The Creating Helpful Incentives to Produce Semiconductors (CHIPS) for America Act was enacted in FY21, yet remains unfunded. Industry, academia, and government agencies continue to analyze the problem and provide key recommendations. Still, no agency or government leader has emerged to align numerous stakeholders and created a cohesive strategy. Over a decade has passed since the U.S. first identified this wicked problem. The United States and its partners must act to protect global markets and national security interests or risk losing the technical edge in semiconductors to China.

This paper recommends establishing a governing organization to lead efforts to bolster the nation's semiconductor related security posture, build alliances and partnerships to ensure resiliency, and reinvigorate the global rules-based order. Additionally, this paper recommends short-term solutions and refinements to current policy actions to resolve DoD and national security requirements.

Taking the Reins

A semiconductor predicament is roiling the free world and threatens to stymie national defenses and economies. Collectively, the U.S. and its allies cannot produce or secure a reliable supply of the semiconductors required for critical national security needs and economic growth in the future. Recent supply chain disruptions and challenges during the height of the COVID-19 pandemic demonstrate the risks to the U.S. of an unguided, intricate, fragile, and global semiconductor ecosystem. China's maneuvers to seize control of the industry through predatory practices amplify these risks, counter the current rules-based world order, and potentially threaten U.S. national security. Over the past 30 years, the U.S. has watched the migration of semiconductor manufacturing capacity to China and other parts of Asia. It can remain complacent no longer. The U.S. and its allies must remain in the lead of the semiconductor industry to protect national interests and maintain the rules-based world order.

The U.S. must work in tandem with its allies to build an alternative semiconductor ecosystem that diffuses, if not counters, the threat China poses. It must lead with a sense of urgency to prevent losing more ground to China. Building such an ecosystem will require a systematic, coordinated effort by government, industry, and academia to bolster U.S. national competitiveness. A concomitant effort is also needed to strategically leverage 'friend-shoring' with our allies to construct a robust and resilient ecosystem, as well as immediate, remedial efforts to secure reliable access to semiconductors critical to national defense.

To justify this assertive approach, this paper first explains why assured access to semiconductors matters. It then probes this predicament as a wicked one, discussing both the dynamics of the problem itself and those influencing possible solutions, and assesses current efforts. The paper then defines this bolder approach, providing recommendations on how to build this alternative semiconductor ecosystem.

Part I: Why Reliable and Secure Access to Semiconductors Matters

Access to semiconductors is critical because semiconductors drive virtually every modern electronic device today, from cellphones and computers to washing machines, refrigerators, electric vehicles, to military weapon systems. These tiny, "smaller than a postage stamp" electronic devices, commonly thought of as the brains of modern electronic devices and systems, are foundational for advanced and emerging technologies, such as AI, quantum computing, IoT, cloud computing, and fifth-generation (5G) telecommunications.[1] The Department of Commerce (DOC) declared recently: "Semiconductors are a strategic resource critical to our economic prosperity and national defense.... "[2] Specifically, semiconductors are a strategic resource in defense, critical infrastructure, and the economy.

First, semiconductors are vital to national defense. As the Deputy Secretary of Defense explained, "…advanced weapons systems such as missiles, jets, lasers, robotics, and much more now incorporate complex and sophisticated technologies that require microchips to develop and field."[3] More specifically, the DoD requires State of the Practice (SOTP) (10-90nm) and Legacy (greater than 90nm) semiconductors for current defense needs. In contrast, access to State of the Art (SOTA) (<10 nanometer) semiconductors is essential for the evolving character of war. [4] The Intelligence Community also requires semiconductors to collect, process, analyze, and store increasing amounts of data and information.

Second, semiconductors are vital components of all 16 critical infrastructure sectors identified by the U.S. Cybersecurity and Infrastructure Security Agency (CISA), from communications to the financial system to healthcare.[5] Critical infrastructure also requires reliable, secure access to semiconductors. That critical infrastructure is often private sector or quasi-governmental only, complicating the risks and solutions and reinforcing the urgency of remediating these challenges.

Third, semiconductors are essential to U.S. economic power, which, as the response to Russia's invasion of Ukraine demonstrates, is integral to the U.S. national security toolkit. As the National Security Strategies of both the Trump and Biden Administrations have affirmed, "economic security is national security" because "a strong economy protects the American people…and sustains American power."[6] Semiconductors are not just a significant engine of U.S. and global economic growth and job creation, they are a growing one.[7] Analysts expect global semiconductor revenues to increase from $600 billion in 2021 to over $1 trillion in 2030.[8] In 2020, U.S.-headquartered semiconductor firms had semiconductor sales of $207.9 billion globally, capturing 47.2% of the global market.[9] According to the Semiconductor Industry Association (SIA), the U.S. semiconductor industry accounts for over 277,000 direct U.S. jobs and over 1.6 million indirect and induced U.S. jobs and has created almost $250 billion of value for the U.S economy.[10]

Fourth, semiconductors are essential to emerging technologies that will drive the U.S. and global economies of tomorrow.[11] Forecasts highlight that industrial IoT alone will comprise 22% of the semiconductor market, and mobile devices (5G) 28%.[12] Emerging technologies can create a rapid inflection point, disrupt current technologies and create a significant disadvantage to companies and countries that are unprepared to adapt.

Finally, semiconductors interact with national security in another crucial way: geopolitically. China's geopolitical aspirations and recent actions shift reliable and secure access to semiconductors into an elevated national security concern. As discussed in more detail below, China may soon control significant portions of semiconductor production, including the legacy nodes critical to DoD. China also has the proximity and capability to disrupt or exert control over the vast majority of the global semiconductor ecosystem due to the high concentration of production in East Asia. Muting China's ability to manipulate semiconductors for geopolitical gains is vital for national security. (See Appendix Section I for further detail.)

Part II: A Wicked Problem

The semiconductor predicament confronting the U.S. and its partners is wicked. It "lack[s] clarity in both [its] aims and solutions, and [is] subject to real-world constraints which hinder risk-free attempts to find a solution."[13] As with all wicked problems, defining the semiconductor predicament is as challenging as solving it, in part because most elements are intertwined.[14] This paper will use Michael E. Porter's 'Diamond of National Competitiveness' model to frame the discussion.[15] (See Appendix Section II for Porter's Diamond.)

The problem. Three interrelated dynamics drive the inability to establish a reliable, secure supply of semiconductors: a rising and more aggressive China; the global dispersion of the value chain throughout the ecosystem; and the shallow value chain.

China**.** Senior U.S. military officials describe China as a 'pacing threat' for the military.[16] China is also a pacing threat for the U.S. economy and, strikingly, for semiconductors. China has used government policies and funding to build out its national competitiveness in the industry to meet 80% of its domestic demand by 2030.[17] China also aspires to stifle others' national competitiveness in semiconductors.

China continues to leverage government policy to transform its factor conditions, incubate supporting industries, and nurture its firms through aggressive subsidies and incentives ($150 billion in incentives from 2014 to 2030).[18] China also uses protective policies and malicious practices designed to suppress others' national competitiveness. China uses its robust and growing demand conditions (24% of global consumption and growing) as an asset and a weapon internationally to siphon off resources, attract foreign firms, and stifle competition from other nations.[19] It works the Diamond and protects its Diamond aggressively.

Indeed, China has employed similar approaches to great effect, destroying several U.S industries and rendering consumers reliant on Chinese products. For example, U.S. laboratories developed photovoltaic (PV) solar capability. The U.S. government sought to increase national competitiveness, focusing on firm strategy and rivalry, heavily assisting firms such as Solyndra, and improving demand conditions by providing tax incentives for homeowners to install the panels.[20] The Chinese government, however, offered more aggressive incentives for its domestic PV firms and implemented questionable labor practices, targeting firm and factor conditions.[21] China then sought to distort others' national competitiveness by dumping PV panels far below U.S. and European manufacturers' price points on the global market. Non-Chinese companies could not compete. Consequently, China now dominates the PV market with an estimated 71% of the global production capacity in 2020.[22] A similar scenario with semiconductors would be far more devastating given their integration and value across other industries.

Another significant concern to U.S. national security is access to legacy and obsolete chips. DoD weapons systems still primarily rely on these chips but do not generate enough demand for U.S.-based firms to find it economically viable to produce them. Consequently, China is the primary source of new and refurbished legacy chips. They continue to grow in this market with 19 new factories centered on the 20-45nm nodes under construction. If China decided to restrict access to these nodes, it could potentially exert leverage over U.S. weapon systems.

Chinese geopolitical aspirations pose a further threat to semiconductor access. Taiwan is the most obvious example of a critical element in the value chain. It produces 92% of the world's SOTA logic chips.[23] China has repeatedly asserted that Taiwan is a rogue province. It views its reunification as part of the Great Rejuvenation.[24] Even if the Chinese did not take control of Taiwan, an attempted reunification or other confrontation across the Strait of Taiwan provoking

U.S.-China geopolitical tensions would devastate the U.S. and global economy by disrupting or stopping the supply of semiconductors from Taiwan.

More generally, China's geopolitical aspirations make real the possibility that China might weaponize access to semiconductors to achieve its ends. China can do so given that more than 80% of semiconductor production now takes place in Asia, primarily in China, Taiwan, and South Korea. Importantly, only South Korea and Taiwan manufacture leading-edge chips 10nm and below.[25] While plans to build foundries for those nodes in the U.S. are moving forward, proximity, capacity, and geopolitical aspirations still mean China is a looming national security concern. These dynamics also point to the necessity of dispersing the concentration of semiconductor capability across the globe.

Geographic dispersion and concentration**.** The geopolitical challenge from China is only one reason the geography of the semiconductor value chain hampers the ability to ensure a secure, reliable supply of semiconductors. That a semiconductor expects to cross international borders more than 70 times during production creates vulnerability to disruption from increasing severe weather events and other sources of instability. For instance, the Russian invasion of Ukraine has raised the prospect of shortages of two critical gases for production, neon, and palladium. Neon is primarily produced in Ukraine, while Russia is a significant producer of palladium. (See Annex 1 for a deeper discussion).

The industry continued to evolve due to the capital required to produce at scale and the high-tech and high volumes needed to be profitable. These requirements precipitated a change in firm strategies in the 1990s resulting in two complementary phenomena: the industry disaggregating into segments of the value chain and a high degree of geographic concentration of these segments. No country in the semiconductor value chain has complete independence.

Disaggregation. Specifically, the industry disaggregated along the following segments of the value chain: (1) Research and Development (R&D); (2) Design, where companies translate requirements into logic and circuit designs; (3) Fabrication, in which large plants (fabs) manufacture semiconductors; and (4) Back-end assembly, testing, and packaging (ATP), where companies separate the wafers, create the chips, and quality-control.[26] As of 2021, most firms have transitioned their business model to reflect this and are either a design (fabless) model or a manufacturing model (foundry and/or outsourced assembly and test companies or OSATs).[27] There are only a few firms, like Intel that continue to do both design and manufacture (IDMs).

Geographic concentration. Maximizing performance led each firm to migrate to where conditions were most favorable, grouping geographically into concentrated clusters. Consequently, manufacturing capacity largely moved from the U.S. to Asia for improved factor and firm conditions: operating costs are approximately 25-50% less, labor costs are up to 80% less, and government support from regulatory to monetary is high.[28,29] There is further concentration of market segments by end-use applications. For instance, smartphone-related semiconductors are concentrated in South Korea, and other electronics in China and Taiwan.[30] The U.S, more attractive for R&D, continues to lead the world in semiconductor design and R&D, supporting roughly 60% of worldwide chip sales.[31] Put another way, this geographic concentration now reflects national competitiveness in segments of the value chain. To shift the geographic concentration in a meaningful, enduring manner (i.e., in a manner that diffuses the influence of China) requires addressing national competitiveness, or 'working the Diamond' for the relevant segments.

Shallowness of value chain. The complexity and capital intensity of the semiconductor industry also led to another consequence: a 'shallow' value chain. This shallow value chain elevates risks of disruption and manipulation of the semiconductor industry, whether by China or another nation seeking advantage. This ‘shallowness,’ moreover, conveys power to firms themselves over national and global wellbeing and security.

Like its geographic dynamics, the semiconductor industry’s shallow value chain reflects a structure maximized for performance. Barriers to entry are particularly high in capital-intensive components of the value chain, such as fabrication. The cost of a new fab facility can reach $20 billion, representing approximately 20% of the value of the products compared with a 4% average across other manufacturing sectors.[32] Consequently, the fabrication segment is oligopolistic, with the leading-edge nodes a struggling duopoly between the Taiwan Semiconductor Manufacturing Company (TSMC), which holds 92% of the capacity, and Samsung with the remaining.[33]

Similarly, input suppliers, such as substrates, silicon wafers, and equipment, also have a similar competitive structure. For instance, the top four manufacturing equipment suppliers, ASML (Netherlands), Applied Materials (U.S.), Tokyo Electron (Japan), and Lam Research (U.S.), command 65% of the sector's revenue.[34] ASML is the only company in the world capable of producing extreme ultraviolet (EUV), which is essential to creating lower-node chips such as those produced by TSMC and Samsung.[35] There are similar patterns with substrates, gases, and other inputs due to regulatory challenges related to extraction and production.

Segmentation and geographic concentration of the value chain means that there is not one industry or market structure. Instead, it is segmented into inter-related ‘sub-industries.’ These ‘sub-industries’ interact through power dynamics akin to separate industries. While other, less capital-intensive segments of the value chain like design and even packaging enjoy a competitive structure, the oligopolistic and duopolistic segments ultimately control access to semiconductors.

This lack of redundancy in the value chain because of sub-industry structures creates an overreliance on a few firms, aggravating the challenges posed by geographic concentration. Shallowness as a structural feature indicates that deepening the value chain will require a change in the industry calculus. For example, if fabrication foundries are disrupted, or ASML is not able to provide equipment, the ability to find substitutes is limited at best, and the consequences for the supply of semiconductors are significant. Interestingly, the combination of China and the disruptions experienced throughout the COVID-19 pandemic appears to have begun to change industry conduct. Firms and governments appear to believe that the operating environment has changed sufficiently that creating ‘redundancies’ is an essential hedge for performance, and begins to build in resiliency. TSMC, for example, is building a leading-edge foundry in the U.S. Still, these efforts are isolated and not systematic.

The contours of a solution. Collectively, these three interrelated dynamics begin to point to a solution. They signal that disparate, piecemeal policies by countries will have little impact; they only will nibble at the edges of the problem. To counter China’s threat requires transforming the geographic and competitive structure of the industry (and sub-industries) to support diversification beyond Asia and amongst firms.[36] Doing so will need countries to coordinate their government policy to ‘work their Diamonds’ and ‘protect their Diamonds’ in as disciplined a manner as China does to build an ecosystem that can counterbalance China’s. Ultimately, then, muting China’s threat requires building an alternative ecosystem.

Building an alternative semiconductor ecosystem to effectively diffuse the power of China (or other unfair competitors) is the other wicked element. Building such an ecosystem requires identifying the stakeholders, establishing relationships, and ensuring its functioning and flourishing, in this case, to successfully counter China. More specifically, the U.S. must navigate three key, interrelated elements successfully: building an alliance of stakeholders that can collectively ‘work’ and ‘protect’ their Diamonds successfully; bolstering its national competitiveness to ‘work’ and ‘protect’ its own Diamond; and creating the structures and systems to lead, advance, and sustain these efforts.

This is not a solo journey. Before going further, it is necessary to reaffirm that 'onshoring' the complete semiconductor value chain to the U.S. is not viable. From a cost perspective, it is unrealistic. For the U.S. to be self-sufficient would require an upfront cost of $350-420 billion and an incremental annual cost of $5-15B.[37] From a technical perspective, it is impractical. The complexity and breadth of the production process also mean that a single firm or nation cannot be fully self-sufficient.[38] Over 30 types of semiconductors exist. Manufacturing them involves 300 inputs and 50 types of equipment. The manufacturing process itself has hundreds of steps and can require up to 3 months to finalize a single wafer of chips. From a policy perspective, complete 'onshoring' will be ineffective. Rather than counter China, it would likely enhance China's influence as U.S. policy and funding would focus not on bolstering national competitiveness in a global industry or countering China's influence but on subsidizing and incentivizing domestic firms.

Thus, U.S. policy should focus on the approach outlined in the previous section: allying to build an alternative semiconductor ecosystem that undermines China's efforts and influence by collectively using government policy to favorably transform the industry's conduct and structure and protect against China's predatory behavior.

<u>Building an alliance.</u> Allying with countries to coordinate their government policy towards these ends requires not simply a set of ad hoc, transactional partnerships. It requires a more sophisticated partnership that is geopolitically grounded and economically focused, able to coordinate complex government policy and navigate the complexity and interdependence of the value chain to ensure the alternate ecosystem is competitive technologically and economically. The partnership should be a formal alliance of like-minded nations focused on countering China's influence, protecting the rules-based world order, and building resiliency.

One of the most challenging parts of building the alliance is determining how the value chain will be distributed across the alliance to maximize efficiency while ensuring redundancy. For the U.S., this raises the question of what elements of the value chain does the U.S. feel is critical to ‘onshore,’ what to ‘friend shore,’ and where to accept risk and leave as is. Answering these questions necessitates understanding not merely what elements are most valuable today to the U.S., but also from where to generate innovation so the U.S. could not just compete but lead. It requires understanding where the U.S. is competitive and where it aspires to be and realistically can be competitive, or where the U.S. wants to work its Diamond.

Rebuilding the Diamond– strategically. China’s efforts to manipulate the semiconductor industry and undermine others’ national competitiveness come when the U.S. is not well-positioned to counter. The U.S. struggles to be competitive in semiconductor manufacturing, from fabrication to ATP. The U.S. share of fabrication shrank from 37% of global capacity in 1990 to 12% in 2020 and its share in ATP is currently stalled at 2%.[39] Still, the U.S. has a significant share of equipment manufacturing (41%).[40] The U.S. has no leading edge (<10 nm) fabrication capacity. This lack of national competitiveness in semiconductor manufacturing traces to factor conditions, such as high domestic labor costs, and unfavorable conditions governing firms, like high taxes and regulatory compliance costs that have plagued other manufacturing-related industries.[41]

At the same time, the U.S.’s continued leadership in the human capital-intensive components of R&D and design is not assured. This is largely due to challenges in maintaining a sufficient labor force in science, technology, engineering, and mathematics (STEM) and relevant trades (e.g., plumbing, HVAC, and construction). While the U.S. houses 23 of the top 50 electrical and electronics engineering programs globally, and eight of the top ten, are in the United States,[42] academia has not been able to increase domestic interest in semiconductors. For example, the number of American students enrolled in semiconductor-related graduate programs (around

90,000) has not increased since 1990; in that same period, international students nearly tripled from 50,000 to 140,000.[43]

Not only does the U.S. education system not produce enough STEM graduates for the industry, but the industry struggles to compete for them with Silicon Valley, cybersecurity firms, and high tech demands from virtually every other industry. The U.S. is also short trade workers to build, expand, and maintain manufacturing facilities. These shortages undermine competitiveness in another way: they generate salary premiums for these workers, increasing operating costs further, which contributes to the movement of low-margin production components to countries with more favorable conditions.[44]

Overall, the U.S.'s Porter's Diamond for the semiconductor industry shows the U.S. is competitive in the front-end components, but that factor and firm conditions are hampering the U.S. from expanding its competitiveness and the erosion of a factor condition, human capital, threatens current strengths. The U.S. cannot, and as the previous section indicates, should not attempt to become competitive across the semiconductor value chain. Instead, as noted, the U.S. needs to determine where it wants to be competitive, whether to maintain or build that competitiveness and to 'work and protect the Diamond' appropriately. Given that the U.S. wants to counter China's leadership, the U.S. needs to compete in components most likely to innovate.

Innovating for tomorrow – new technology and physics. China seeks to reach parity with "the United States in semiconductor technology, artificial intelligence, and quantum computing" within the next decade.[45] "These core technologies will fuel future innovations in other fields essential to future economic growth."[46] AI seeks to replicate human understanding and decision-making, while quantum computing unleashes the exponential power of computing – dwarfing the capabilities of today's most advanced supercomputers. Combined, these two semiconductordriven technologies could redefine our reality and unlock expansive defense capabilities and economic growth.[47]

As semiconductors approach the scientific boundaries of physics (the end of 'Moore's Law'), innovation will necessarily and increasingly come from architecture and packaging. Leveraging new semiconductor innovations like heterogeneous integration, where combinations of chips of different functions (memory, logic, analog, etc.), will advance capabilities using current technology.[48] Such innovations expand the tools for new functionality and better performance. They promise to transform the structure and conduct of the industry, moving the industry from a focus on node size and foundries to architecture and packaging, with a reliance on SOTP nodes and an elevated role of ATP and OSATs. From a national competitiveness perspective, these dynamics indicate that the U.S. should prioritize competitiveness in packaging and guard and expand competitiveness in SOTP nodes.

The next innovation/R&D. These dynamics also reinforce the necessity to ensure competitiveness in the value chain component of R&D. Semiconductor's role in emerging technologies requires strengthening research into new materials, designs, and eventually semiconductor replacement to remain competitive.[49] Using R&D to achieve such disruptive technology would transform the landscape of the industry, and potentially derail China's plans. This approach is "vital to guaranteeing superior military capabilities, generating obsolescence in adversary capabilities, and boosting the U.S. economy."[50]

Based on this analysis, the U.S. should focus on building its competitiveness in packaging, ensure its R&D leadership, and maintain its fabrication capacity. Looking at Porter's Diamond, doing so will require addressing the challenges in the factor condition of human capital and firm conditions related to firm rivalry and conduct. Also, the U.S. does not necessarily have an ecosystem of supporting industries, like the required substrates and materials. Developing these, however, seems impractical due to regulatory and political issues and most could be provisioned through alliances and partnerships.

The U.S. is competing in an industry where countries have aggressively sought to increase their competitiveness by wielding government policies to attract industry and have the domestic political tolerance for such activist policies. Countries in Asia, for instance, have targeted firm conditions, offering substantial government incentives to offset costs such as construction and utilities to attract businesses to their borders and often have lax environmental, health and safety standards.[51,52] To compete, the U.S. will have to find creative solutions aligned with culture and politics.

Protect the diamond. While building out national competitiveness is vital, so is 'protecting the diamond.' Protecting the diamond is focused on two types of activity. First, ensuring reliable and secure access to components critical to national security. Second, taking measures to directly counter efforts to undermine the U.S. or its allies' competitiveness, especially China's predatory practices.

The first and most immediate requirement is ensuring reliable and secure access to legacy nodes needed to support weapons systems that are no longer in production where the risk of counterfeits when resourcing refurbished chips is high. The opaque nature of the supply chain for other semiconductors that are still in production raises concerns about security and performance, pointing to a need to create standards and transparency for a secure supply chain.

China's predatory practices include pulling multiple levers of national power to gain an edge in the semiconductor industry and they will do almost anything to reduce China's dependence on foreign-made microchips.[53] The Chinese government employs production targets, subsidies, tax preferences, and trade barriers to support the domestic semiconductor industry.[54] Additionally, Chinese state-sponsored companies work to acquire leading-edge foreign technology through forced technology transfer agreements, IP theft, and talent poaching.[55] Finally, China is leveraging international talent and research to gain a domestic advantage. For example, China's top technology firms have U.S. R&D centers that partner with universities globally, hire tech talent, and participate in open-source technology platforms, such as RISC-V, to access U.S. semiconductor expertise.[56] China's industrial policies, IP practices, and forced technology transfer play a substantial role in undermining foreign competition and will likely cause market distortions.[57]

Creating the organizing structure. The U.S.'s internal challenge compounds these dynamics. It struggles to design and implement government policy to improve national competitiveness. The U.S. government does not have one centralized entity responsible for industrial insight, policy, oversight, and support. A milieu of localities, states, and federal agencies drive actions, regulations, and policies affecting the industry without much coordination. However, efforts lack whole-of-government coordination. This lack of centralized coordination hampers efforts to support the industry to further U.S. interests.

Interestingly, the U.S. faced a similar predicament in the late 1980s. The main differences were that the competitor was an ally and the competitiveness challenge was discrete. Thirty years ago, the U.S. produced approximately 37% of the semiconductor industry's global production. In the 1980s, the U.S.'s share of global production fell below 40% when Japan's memory chip industry caught up to the U.S.'s technologically.[58] A rapid loss of both manufacturing capacity and technological leadership abroad reflected an erosion of the U.S. national competitiveness.[59] Drawing upon recommendations in 1987 by the Defense Science Board's Task Force on Semiconductor Dependency, the U.S. government response was two-fold. It concluded the 1986 U.S.-Japan Semiconductor Agreement to open up the Japanese semiconductor market to the U.S.

and in 1987 supported the formation of the research consortium, SEMATECH, which focused on enabling the U.S. to regain technological leadership.[60]

The first part of the government response, the bilateral agreement for market access with Japan, clearly is not viable with China today though the principles the agreement reflects – of muting influence, shaping the ecosystem, and expanding competition – are relevant. The second part of the government's response, SEMATECH, is germane. Initially composed of 14 U.S.-based semiconductor manufacturers, SEMATECH partnered with the U.S. government to advance U.S.-based semiconductor manufacturing technology and capability beyond its competitors and promote global U.S. economic and technological competitiveness.[61] SEMATECH is generally viewed as contributing to the revival of U.S. national competitiveness. As such, it provides lessons for building a solution to the more wicked predicament of today.

One of SEMATECH's most noteworthy accomplishments, for instance, was its role as the architect of the National Technology Roadmap. This roadmap served as the shared vision to guide semiconductor-related research and development across the government, industry, and academia. Such a roadmap and collective focus, as will be seen below, are notably missing.
Similarly, SEMATECH's successful approach of setting ambitious industry goals and leveraging diverse resources to accomplish them, such as reducing the miniaturization cycle from three to two years, provides a valuable model for both the international ecosystem and domestic efforts to restore competitiveness. While SEMATECH has garnered criticism as creating an exclusive club that stifled competition, it is a useful model to design industry-government-academia efforts to restore competitiveness.[62]

Part III: Understanding What is Being Done Now

The recent pandemic-related semiconductor shortage focused the world's attention and spurred action. These initiatives, while laudable, do not systematically tackle the challenges confronting the U.S. to reassert leadership or ‘work and protect the diamond’ in the semiconductor industry to secure reliable access to critical semiconductors and build an alternative ecosystem to counter China.

Current efforts to build alliances. The Biden administration’s efforts to build alliances and partnerships are focused on creating more favorable conditions governing firms by establishing global standards for semiconductors and mitigating challenges with related industries by building supply chain resiliency. Yet, these efforts, such as those with Europe, seem more opportunistic than systematic. There also are efforts to build alliances to counter China. In East Asia, the U.S. is working to build a semiconductor technology alliance with Taiwan, South Korea, and Japan to counter China.[63] In southeast Asia, the Biden administration’s “China + 1” policy, designed to encourage a shift in firm strategy to both build redundancy and mitigate China’s influence by incentivizing U.S. companies with Chinese manufacturing facilities also to build manufacturing in another Association of Southeast Asian Nations (ASEAN) country, has resulted in shifts of production from China to Malaysia, Thailand, the Philippines, and Indonesia.[64] While vital, these efforts are generally disparate and do not constitute the coordinated, comprehensive effort necessary to counter China.

Current efforts to build national competitiveness. Unlike the era of SEMATECH, government, industry, and academia lack a common vision and are not systematically directing resources to address the semiconductor predicament. Instead, they are generally independently working to improve or support factor conditions, industry structure, and supporting industries to maintain competitiveness. The result is suboptimal. Illustrative examples are provided in the status of R&D and firm conditions.

Since 1980, federal funding to R&D has shrunk from between 48% – 65% to approximately 21%, generally focused on supporting research to extend the life of current semiconductor technologies and to develop the underpinnings for successor technologies.[65,66] Business-funded R&D reached approximately 70% in 2019.[67] While the business-generated R&D paradigm is worthwhile and has led to disruptive innovations, its predominance means that the federal government is adopting innovations rather than creating or driving them. As explained above, increased federal investment in R&D is essential to boosting innovations and gaining competitiveness in an industry where the U.S. is disadvantaged by high operating costs, a competitively sought workforce, and a lack of organically sourced strategic materials.[68]

Similarly, government policy has sought to address firm conditions through discrete investments in specific capabilities.[69] The most active area of government policy to transform firm conditions has been at the state and local levels, which generally are on the front lines of semiconductor firm strategy and investment. For example, over several decades and with differing governors, New York has built up its Capital Region's educational institutions and provided subsidies to attract the semiconductor industry. Texas has attracted the semiconductor industry through business-friendly tax policies and a more hands-off approach, with its local stakeholders in Austin taking the lead. Both New York and Texas' strategic approaches have proven effective but have lacked synchronization with federal incentives.

Congress could provide some structure and guidance through legislation. While it is actively engaged in significant legislation and appropriations to improve American semiconductor competitiveness, Congress is relitigating the authorizing legislation, the Creating Helpful Incentives to Produce Semiconductors for America (CHIPS) Act, passed in January 2021. CHIPS seeks to improve U.S. national competitiveness, focusing primarily on firm structure and rivalry, by incentivizing manufacturing, and factor conditions, including R&D, and workforce training. In addition, it echoes SEMATECH in calling for coordinated semiconductor R&D amongst a variety of semiconductor firms with U.S.-based operations.[70] The current legislative debate generally is focusing on the topics of this paper: where to compete and what government policies to use but also the implications of incentives and subsidies on the economy and the deficit as well as if the efforts outlined in the various legislation are even sufficient to counter China's efforts.[71,72,73] (See Appendix Section III for a detailed analysis of the challenges of pending legislation.)

Firms are also changing their conduct, seeking to build redundancies or re-shore capabilities. In January 2022, Intel announced it will invest $20 billion in two new plants in Ohio to make advanced chips, the first step to a "mega-site" that can accommodate eight chip factories costing $100 billion.[74] Government, industry, and academia efforts are independently moving in the right direction; however, they lack a national strategy. There is an opportunity for a centralized organization to synchronize these efforts at a much larger scale.

Part IV: Finding a New Approach

National Competitiveness-Factor Conditions

U.S. competitive advantage hinges on appropriate levels, and proper vectoring of government policy and funding. The strategy must focus on the factor condition of R&D as previously discussed to unleash the benefits of emerging technologies and discover solutions to alter the state of the semiconductor industry.[75] Additionally, the factor conditions of human capital and alliance deserve attention.

Similarly, securing workforce talent is a required factor condition for competitive advantage in the semiconductor industry, which the U.S. has struggled to nurture. To achieve this, the U.S. must make concerted efforts to improve human capital to strengthen the global semiconductor industry and its supply chain. Early, sufficient, and consistent investment in industry-related fields of study will boost the necessary skills to compete in this industry. Through policy initiatives strengthening STEM education, as well as training programs to give workers skills that align with technological advancement, politicians and community leaders can shape human capital into economic growth and develop the workforce to meet the pace of innovation.[76]

Though the U.S. has invested in STEM education, it requires more attention as the semiconductor industry demands more talent. Investments of approximately $3 billion in STEM education have facilitated targeted early learning and instruction, STEM degrees and careers, and educational R&D. While degrees trend upwards, K-12 performance on the National Assessment of Educational Progress has shown little improvement in primary education in the past decade.[77] To develop human capital to lead the global technology race, the U.S. must establish a comprehensive national semiconductor strategy directed at stimulating interest and increased skills in pre-college students.[78] Policies and programs focused on a bottom-up holistic approach will help regain the market to become less reliant on China. This plan has to focus more diligently on STEM at the primary school level to build a sustainable pool of talent.

Alliances and partnerships provide an additive factor condition to ensure industrial competitiveness. Not only do these relationships drive rivalries and competition to spur innovation, but they also provide resiliency to mitigate industry disruptions or assaults. For example, it is paramount to build distributed end-to-end semiconductor manufacturing capacity in allied nations to support commonly shared defense systems and critical infrastructure. This commitment would ensure regional allied nation access to critical chips, while providing supply chain diversification and redundancy. Thus, strengthening interdependence and promoting democratic values. U.S. policy must account for these redundancies to adapt to industry-related global challenges like supply chain vulnerabilities, natural resources, and energy concerns. Reliance on allied and strategic partner burden-sharing in the high-cost semiconductors industry is essential. International cooperation can bolster sectors such as manufacturing, prototyping, and packaging and drive a new paradigm for resiliency and economic security.

Allied nations must take precedence over partners to ensure trusted, standard, and legally codified agreements for manufacturing. However, expanded partner nation relationships, trade agreements, and initiatives are vital and require increased attention. Through this soft power approach, the U.S. reaps substantial economic benefits and also strengthens the competitiveness of the global network. Leveraging this network to create and uphold treaties, trade agreements, and industry initiatives and standards will situate the U.S. to reclaim its leadership role within the semiconductor industry. (See Appendix Section IV for examples.)

National Competitiveness-Firm Strategy

Government investment has become necessary to maintain or gain a competitive advantage in the advancing and costly semiconductor industry. These investments are crucial as fabrication facilities cost $10-40 billion, and the ever-vital lithography machines cost hundreds of millions of dollars.[79] Additionally, these facilities consume energy at a rate upwards of 100 megawatt-hours per hour, costing $20-30 million dollars a year.[80] The Chinese government, for example, incentivizes and subsidizes this industry more than any other country.[81] Nations require substantial, consistent, and organized governmental investment to compete and ensure security and sustainment.

The U.S. government must show fiscal restraint, identifying areas for strategic investment while avoiding an industry spending war with China. U.S. semiconductor industrial policy and investment should focus on maintaining the comparative advantage in design and strengthening advanced test, assembly, and packaging capabilities, while strongly reinforcing workforce development and R&D. Government incentives and subsidies need specificity enough to shape national strategy within the industry but be broad enough to encourage a nationally competitive environment- promote competition, not pick national champions. This approach will leverage current industrial trends, like system on a chip (SoC) and heterogeneous integration and talent development, and allow transformational innovations to alter the semiconductor industry.[82]

A centralized entity to manage the national semiconductor strategy and lead allied and partner efforts is critical. This entity will require domestic coordination from industry, academia, and government to achieve national semiconductor objectives. Similarly, strong alliances and partnerships across the globe will build trust in supply chains and create capabilities independent from China, ensuring U.S., allied, and partner nation security and economic growth in the future. This entity must coordinate to secure natural resources and materials to mitigate risk within a volatile global market. The U.S., allies, and partners must have assured supply chains for strategic materials to compete. This is possible through bolstering an organic capability to mine and process available natural resources and re-enforcing relationships with our allies and partners to diversify strategic material access globally.

The U.S. cannot, and should not, compete in every facet of the Porter Diamond. Instead, the U.S. must smartly navigate the paradigm and prioritize efforts to regain a competitive advantage in the semiconductor industry. The U.S. must prioritize creating a central body responsible for developing and executing a comprehensive semiconductor strategy. This strategy must focus on maintaining a comparative advantage in chip design and technological development. Intently focusing on the factor conditions of R&D and human capital will ensure leadership in these areas. The strategy must ensure access to supply of critical chips. Onshoring or friend-shoring end-to-end manufacturing capabilities for specific defense and critical infrastructure-related systems will mitigate national security vulnerabilities. Leveraging the factor conditions of international alliances and partnerships and governmental industry stimulation (incentives and subsidies) will boost resiliency in the supply chain and mitigate risk while furthering opportunities for economic growth and competitiveness. Finally, the national semiconductor strategy must rely on a structure and design to promote industrial leadership and viability.

Focusing on a balanced public-private partnership strategy and structural approach will help determine where national investments or divestments are required to further national competitiveness within the industry. Undoubtedly, the demand conditions for competitiveness are strong as semiconductors will remain the heartbeat of current and emerging technologies. However, more demand-side pressure is required to guarantee trusted and security-assured chips. Now is the time for the U.S. to act and shift the balance of the semiconductor industry.

Part V: Recommendations

The primary objective is to protect U.S. national security and rebuild U.S. national competitiveness in the semiconductor industry, focusing on countering China's efforts to dominate the industry. The proposed National Semiconductor Technology Center (NSTC) will create a comprehensive national semiconductor strategy and provide the center of gravity for implementation. The CHIPS Act funding appears sufficient at this time. Most of the recommended policy and coordination actions below require prioritizing semiconductors within existing government programs.

Consortium Creation

The U.S. should modify the coordinating structures in the CHIPS Act and establish an umbrella consortium of industry, federal and state government, and academia. This consortium will plan, coordinate, adapt, and act to protect U.S. national security and rebuild U.S. national competitiveness in the semiconductor industry, with a focus on countering China's efforts to dominate the industry.

<u>Mandate.</u> The consortium will act from the national strategy to align federal and state governments, industry, and academic action to advance national security and competitiveness and

serve as the U.S. counterpart to similar international consortia. Congress should empower this consortium to facilitate collaborative research, catalyze cooperative behavior, and drive U.S. semiconductor industrial policy. This mandate includes aligning disparate domestic and international efforts, reinforcing the joint semiconductor dominance of the U.S. and its allies while reducing supply chain vulnerabilities.

Membership. The NSTC will lead the U.S. representation. Core federal government members should include Departments of Commerce, including the National Institute of Standards and Technology (NIST), DoD, United States Trade Representative (USTR), Department of State, and Department of Treasury. The National Association of Governors should select members to include both states with existing and anticipated semiconductor-related clusters (e.g., Texas, New York, California, Ohio). Relevant professional organizations should select industry and academic membership. International allies and related industry groups can nominate as well.

Funding. Funding for this consortium should be a public-private partnership. Proposed congressionally designated investments, such as those appropriated to support the CHIPS Act or its successor, will be leveraged to secure matching industry investments. NSTC will be responsible for modest administrative costs of operations. The NSTC will oversee existing R&D funds from across the government will be coordinated and re-aligned to meet the national semiconductor strategy objectives and consortium goals.

Strategy on Semiconductors

The consortium should execute the semiconductor strategy to ensure reliable and secure access to necessary chips critical to U.S. national security; and compete with and counter China's efforts to dominate the industry. The recommended U.S. strategy should:

- Make choices to improve firm conditions. Leverage trade policy, tax policy, subsidies, and partnership capacity to secure the semiconductor value chain, with the weight of effort on areas of highest vulnerability and priority, currently as follows:

1. Advanced Packaging and Test
2. Printed Circuit Boards
3. Memory Semiconductors
4. SOTP / Legacy nodes
5. SOTA nodes

- Tackle current, emergent issues affecting national defense. To mitigate DoD weapons systems reliance on Chinese chips, DoD should create a reclamation program to reduce risk from refurbished, potentially counterfeit chips on the gray market. DoD will use existing acquisition funding for this requirement.

- Establish policy to grow demand conditions for U.S. and partner markets through a 'secure purchase mandate.' Require member nations to source critical infrastructure components from U.S., partner, or other assured markets. Dual benefits from this program will be increased security for infrastructure and increased private investment. Costs will be borne by existing infrastructure build and maintenance projects. This requirement will be phased in over a decade to signal growing market demand and attract supply-side private investment in U.S. production.

- Add semiconductor manufacturing as a critical infrastructure. The NSTC should play a central role in unifying the efforts to revitalize domestic and international supply chains. NSTC leadership should work with the Department of Homeland Security to establish the semiconductor industry as the 17th critical infrastructure sector.

- Address three key <u>factor conditions</u>: human capital, R&D, and alliances and partnerships.

   1. Human capital. To further develop human capital, strategically expand and deliberately develop STEM interest and opportunities in the U.S. primary education system (K-12th grades) to ensure future technological leadership. Such efforts should be designed based upon an assessment of the Department of Education and industry-funded STEM and semiconductor–related initiatives. The NSTC will oversee the alignment of these existing initiatives to bolster the future semiconductor workforce.

   2. R&D. The U.S. should bolster federal funding for R&D related to semiconductors. From CHIPS appropriations, additional funding should be allocated to government labs and research agencies, including DARPA, to support defense- and national security-related innovations. The NSTC and Consortium should lead the coordination and execution to ensure unity of effort.

   3. Alliances and partnerships. The U.S. should form agreements with allies and partners to compete with and counter China on semiconductors and protect the interests of the rules-based order. The alliance will build a U.S.-led secure global ecosystem, formalizing 'friend-shoring' arrangements, including-supporting industries, codifying joint standard-setting, and aligning security interests. The alliance should expand existing agreements with reliable partners in North

America, Asia, and Europe. The alliance will evaluate the current partner ecosystem to determine multi-national weight of effort and investments.

- Counter Malicious Practices by China through a full range of assertive measures including but not limited to:
    - The Department of Commerce expands the Entity List and broadens export controls to prevent China from acquiring leading-edge technology, like semiconductors.
    - The Department of Justice expands efforts to counter China's IP theft in semiconductors.
    - Consider other measures, such as establishing security or zero-trust standards for critical semiconductors and production processes. Bolster anti-dumping measures and anti-counterfeit efforts, and strengthen Committee on Foreign Investment in the United States (CFIUS).

Conclusion

Implementing the recommended policy adjustments and building a strong consortium to synchronize efforts across allied nations, will enable the U.S. to create a focused, long-term, adaptive strategy to counter Chinese predatory practices and shape a brighter future. Through addressing all aspects of the triple-helix, both in the U.S. and across the free world, the partnerships between government, industry, and allies will shape, secure and improve ecosystems to enable continued growth of the industry. This new, robust semiconductor ecosystem will help maintain the design lead, rebuild manufacturing capacity, bolster the rules-based order, and return the U.S. and its allies to an uncontested technological lead.

Annex and Appendices

Annex I: Semiconductors and Defending Ukraine

The U.S. has a policy of supporting Ukraine and defending Europe. The unprovoked Russian invasion triggered an unprecedented flow of Western weapons, economic aid, and punitive actions against Russia. The U.S. is seeking all available means to support Ukraine in its effort to repel the attack. Since semiconductors are a critical element of all modern economies and military systems, the U.S. can and should exert pressure on global markets to exclude Russia and advance NATO interests. With broad sanctions already in place, but secondary sanctions unlikely to be enforced, the U.S. must work with neutral states to restrict the most critical chips flowing to Russia in secondary ('gray') markets.

The global semiconductor market is approaching $500B per year, while Russia imports a mere $40M of loose chips.[83,84,85] Sanctioning semiconductor exports to Russia will have little impact on the broader market but will likely deal a tactical blow to Russian manufacturing and consumption. Though Chinese exports already represents 70% of Russian semiconductor imports, additional market share is unlikely to provide a strategic benefit to the Chinese semiconductor market.[86] Even supplying all Russian imports, the Russian market only amounts to 0.1% of Chinese production (~$40B/yr).[87] As such, the Russian purchasing power is not of strategic concern with respect to the U.S.-China semiconductor market competition.

Though sanctions do not provide a strategic opportunity (or cost), a suite of tactical opportunities exists. As Russian tanks rolled into Ukraine, the Biden administration sought to "choke off Russia's import of technological goods critical to a diversified economy and Putin's ability to project power."[88] The restrictions on semiconductor exports to Russia target military applications, industrial control systems, and even consumer applications.

Russia is entirely reliant on imported semiconductors for military, consumer, and industrial applications.[89] Though imports peaked in 2018, the subsequent downturn in imports did not reflect an increased domestic supply but rather an inability to compete for supply during the shortage.[90] This systemic shortfall in supply indicates that the sanctions will likely affect Russia immediately.

The Ukrainian invasion has settled into a war of attrition, with Russia losing over 3,300 vehicles, including 600 tanks, 55 aircraft, and 100+ command or radar vehicles.[91] Though Russia maintains a significant depth of reserves, tank losses alone are approaching 20%, representing a significant amount of force.[92] Reconstitution will become a strategic imperative for Russia in the years ahead.

Already, signs of production slow-downs are leaking out. Most recently, the Uralvagonzavod tank manufacturing plant appears to have shut down due to part supply issues.[93] A detailed analysis of Russian supply chains may reveal where semiconductor shortages have the greatest likelihood of inhibiting production lines.[94] Though tank losses are one example, limiting the manufacturing of asymmetric systems (such as consumer drones) is just as critical.[95] Similar analysis should be performed on such consumer systems that may substitute for military systems.

The most significant risk to semiconductor sanction efficacy is sanction evasion through neutral countries like China and India. Though, there are initial signs that China is refraining from large-scale sanction evasion – such as a pause in Huawei supplying Russia – that may be insufficient to prevent Russia from circumventing sanctions. Russia is already rebuilding supply chains to run through friendly countries, and there are limited visible signs in Russia that the sanctions are having an immediate effect. [96,97,98]

U.S. entreaties to allies that Beijing must abide by the sanctions and face secondary sanctions for any "large-scale sanctions evasion efforts or support to Russia to backfill them" are likely insufficient to deter a robust gray-market Russian supply chain.[99,100] Russia's insignificant global share of the semiconductor market also means that a relatively small gray market can supply their needs. If the U.S. intends to use sanctions to prevent reconstitution, limit industrial capacity, and create consumer shortages, then robust enforcement of the sanctions is critical.

The U.S. should continue threatening secondary sanctions as punishment for supporting Russia's war. However, secondary sanctions are unlikely to be approved by partner states, and regardless, the gray markets are difficult to constrain. How can the U.S. best limit Russian access to gray-market, neutral nation semiconductor supply chains? Russian reconstitution and economic activity may be slowed if the U.S. can offer inducements around narrow, targeted blacklisting of critical military chips.

As the most likely to flaunt U.S. sanctions, China and India should be the focus of U.S. inducements and enforcement. Opportunities exist in both India's recent repudiation of Russian military purchases and joint India-U.S. semiconductor manufacturing partnerships. Rather than secondary sanction threat, the U.S. should offer specific benefits such as access to foreign military sales programs or access to semiconductor technology in return for sanctions compliance. Tying U.S.-Indian semiconductor ecosystem integration to sanction compliance may reduce sanction evasion, while benefitting broader U.S. semiconductor market goals of 'friend-shoring.'

Inducing China to enforce gray-market sanctions is more problematic. The U.S. may need to make significant strategic trade-offs to achieve success. The trade-off could be as unpalatable as reducing U.S. rhetoric on Chinese human rights issues to secure Chinese sanction support. Other, less ethnically challenging opportunities are economic inducements such as loosening tariffs. One potential mutually beneficial incentive may be an offer for increased wheat supply (or reduced tariffs).[101] Such an offer may reduce Beijing-Moscow ties, increase Chinese food security, and garner support for the gray-market sanctions.

A potential substitution or alternative source of semiconductors for Russia is through commercial end-item purchases rather than loose chips. Beyond the scope of the semiconductor market, the U.S. should perform an analysis to ensure appropriate sanctions are in place to prevent substituting (e.g., commercial drones for organic Russian drones) or harvesting from imported commercial items. Additional sanctions likely need to go beyond the current U.S.-imposed and voluntary restrictions.[102]

To continue U.S. support for Ukraine, the U.S. will need to reconstitute DoD stockpiles and maintain overall economic strength. Russia and Ukraine are critical exporters of neon, palladium, and platinum, which are all used in semiconductor production. The invasion is disrupting this supply chain.[103] Continuous analysis needs to be performed on U.S. supply chains and stockpiles to ensure those risks do not degrade the international semiconductor market sufficiently to affect U.S. reconstitution or economic strength.

Conclusion. Russia is not a significant participant in the global semiconductor market but is highly dependent on that global market. Russian reconstitution will become increasingly critical to the outcome as the Russian-Ukrainian war drags on. Depending on voluntary compliance or secondary sanctions will not prevent the flow of gray-market semiconductors to Russia. The U.S. must identify narrow sanctions required for success and provide incentives to neutral countries for self-enforcement.

Appendix – Section I

What is a semiconductor?

Semiconductors are tiny, "smaller than a postage stamp," electronic devices, commonly thought of as the brains of modern electronic devices and systems.[104] They are composed of millions of capacitors and transistors that store, move, and process data. Every electronic device has a circuit board usually containing multiple semiconductors of varied complexity and functionality divided into analog, memory, or logic functions.[105] Merriam-Webster defines a semiconductor as a class of solids (such as germanium or silicon) whose electrical conductivity is between a conductor and an insulator in being nearly as great as that of a metal at high nearly absent at low temperatures; thus "the term "semiconductor" comes from their electrical properties that combine features of both insulators and conductors, allowing control of the flow of electric current." [106,107] The term is often synonymous with "integrated circuit," "microelectronic chip" (microchip), and/or "computer chip" and will be used interchangeably going forward.

Evolution of the semiconductor industry

Semiconductors have been around for over 70 years. In the late 1950s, semiconductor manufacturers entered the market in the U.S., swiftly acquiring the market share. In the early 1960s, specialized manufacturers of semiconductor machinery and equipment began to emerge. George Moore observed the emerging semiconductor trend and concluded that computing would dramatically increase. Technological advances will allow chips to become considerably faster, smaller, and more efficient.[108] Moore's Law ultimately became the guiding principle for the electronics industry and a foundation for semiconductor innovation.

During the 1970s, most semiconductor firms followed a vertically integrated business strategy, that included end-to-end processes. Firms that include both design and manufacturing are known as Integrated Device Manufacturers, (IDMs). Large IDMs, such as IBM, designed their own components, manufactured the equipment used in the production process, and used internally produced components to manufacture their microchips.[109] This business model protected IP by restricting the number of people who had access to the chip designs.[110]

Smaller companies began to enter the market in the early 1980s; but by the 1990's, the Semiconductor industry started transitioning. Domestic firms began to take advantage of cheaper labor markets (up to 80% less), operating costs, (25-50% less), and regulatory and monetary incentives from mostly Asian countries.[111] This incentivized U.S. firms to shed less lucrative business areas, and transfer aspects of the industry to Asia, which subsequently allowed Asian countries easy entry into the semiconductor market. With the transition, most countries have now refined their resources to one specific aspect of the semiconductor industry. This has ultimately produced multiple business models and markets.

Associated markets, models, and specializations today include 1) R&D; 2) Design, in which companies conceive new products and specifications to meet customer needs and reduce these ideas to particular logic and circuit designs for manufacture; 3) Front-end fabrication, in which fabs are used to manufacture semiconductors by etching microscopic electronic circuits onto wafers of silicon (or, less commonly, other materials); and 4) Back-end ATP, in which wafers are sliced into individual semiconductors, encased in plastic, and put through a quality-control process.[112] Additionally, the industry has created a healthy equipment/machinery industry that manufactures the Front-end fabrication and back-end ATP equipment necessary to produce semiconductors.[113] Consequently, there is not one industry or market structure. Instead, it is segmented into inter-related 'sub-industries' with differing power dynamics or 'five forces.'

As of 2021, most firms have transitioned their business model to one of the two main stages of semiconductor production, either a design (fabless) model or a manufacture (foundry) model.[114] There are only a few firms, like Intel that continue to do both design and manufacture.

Foundries the most expensive component of the value chain, thus imbuing them with more bargaining power. They are the most capital-intensive component of the production chain; wafer fabrication accounts for 64% of the industry's capital expenditures.[115] Given this, the number, and thus capacity of foundries, are generally more limited.

Technically, a monopolistic competitive structure exists amongst foundries if all three types of semiconductors (memory, logic, and analog) are grouped together. Aggregating, however, conveys a false impression of the foundry industry's competitive structure. In 'leading edge' or newer (logic) nodes, there is a struggling duopoly between the dominant TSMC, which holds about 92% of capacity <10 nm, and Samsung, which has approximately 8%.[116] As nodes increase, the competitive structure generally trends towards monopolistic competition.

Foundries' buyers or consumers, i.e., the firms across the process chain (fabless design firms, OSATs, and IDMs), do have moderate bargaining power. Given the limited foundry capacity relative to demand, this power generally rests with customers with enough scale to command foundry time, like Apple, rather than start-ups.[117] Indeed, scale matters for both the foundries and their customers. Scale enables efficiencies and conveys bargaining power. Consequently, small and medium firms across the process chain or within the ecosystem can face significant barriers to entry, even in relatively less capital-intensive components like design.

Suppliers, though, have significant power. Raw materials and manufacturing equipment both can be highly specialized and from a limited number of firms which creates a level of mutual dependence that mutes supplier power somewhat.[118] SIA estimates that 90% of the value of a semiconductor chip is split evenly between the design and fabrication stages, while the remaining 10% is added during the ATP stage.[119]

The industry continues to grow rapidly as technology enhances and drives demand across multiple industries. Due to rising demand for semiconductor-reliant electronics, industry revenue is expected to continue to grow an at annualized rate of 4.2% to $26.2 billion through 2026 and reach $1 trillion by 2030.[120] However, microchip production now takes "hundreds of steps, with an incredibly complex supply chain linking the raw materials, supply vendors, foundries, and packaging facilities."[121] According to the SIA, in 2016 they estimated large U.S.-based semiconductor firms may have as many as 16,000 global suppliers.[122]

Currently, 87% of the industry's largest exports are from foreign markets: China, South Korea, Taiwan, and Japan.[123] Thirty years ago, the U.S. produced approximately 37% of the global microchip production, but as of 2021, the U.S. only has 12% of the market share for wafer fabrication. The U.S. industry lags behind its Asian-based competitors for manufacturing, as well as other business segments. "In 2019, 100% of the world's most advanced logic semiconductors (< 10 nm) were produced overseas."[124] Taiwan holds the market share for manufacturing at about 77%; although China is expected to take the lead in global production by 2030. In addition to the decrease in market share for manufacturing, the U.S. only has 2% of the market share for testing, packaging, and assembly.[125]

Although the U.S. currently has no production capability for nodes <10 nm; domestic semiconductor companies are the global market leader for the chip design business model, as well as R&D. U.S.-based firm IBM is working jointly with Samsung Electronics to develop cutting edge 2nm technology.[126] According to SIA the U.S.'s comparative advantage in the semiconductor ecosystem are R&D and chip design. While the semiconductor industry is historically cyclical – dependent on technological advancements, product innovations and market imbalances;[127] geographic specialization significantly impacted growth and innovation within the industry. Both U.S. and overseas firms have greatly benefited from the disaggregation of the semiconductor processes, and the economic benefits. Geographic specialization has been attributed to an estimated $3 trillion in global GDP from 1995 to 2015.[128]

Evolution on role of National Security

The semiconductor industry is in a state of flux and teetering on that of a crisis, stemming from the disaggregation. The industry transition into an extensive ecosystem has created a variety of challenges – multiple markets with a such a vast network of firms, have created a complex supply chain with many single source providers, supply chain volatility, and specifically for the U.S. – foreign (China) dependency.

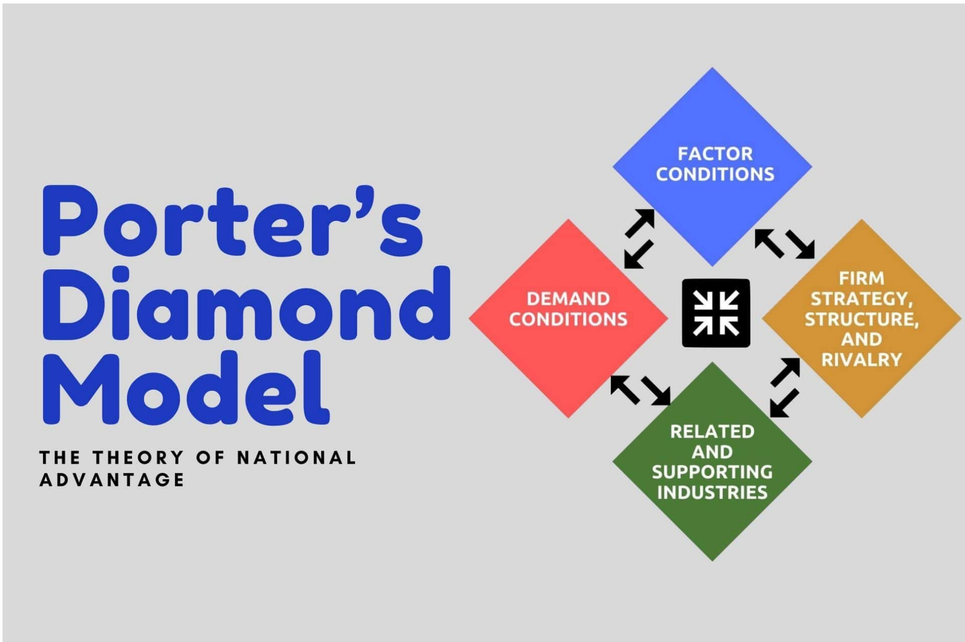
COVID-19 exposed significant weaknesses in the overall supply chain that cannot go unnoticed. However, China specifically has an initiative to establish global industry dominance by 2030 and is thus the greatest threat to the United States. China has been and continues to invest heavily in the full spectrum of the semiconductor industry. Not only have they have created numerous industrial policies and state investment vehicles to successfully incentivize numerous U.S. firms to move their manufacturing to China; China has also successfully reshaped its role and capabilities within the semiconductor industry writ large. Perhaps the greatest concern to U.S. national security is access to legacy and obsolete chips. DoD weapons systems still largely rely on larger nodes and legacy chips (>14nm) and the number of foundries producing legacy chips is quite small. China has been the primary source for legacy chips, and they are continuing to grow in this market with 19 new factories centered on the 20-45nm nodes under construction.

Equipment and tools are a further example of China's efforts to develop a large and advanced semiconductor industry. "In 2014 the five main toolmakers sold gear worth \$3.3bn, 10% of the global market, to China. Today the country is their largest market by a significant margin, making up a quarter of global revenues."[129] In 2021, U.S. firm Applied Materials alone sold \$7.5bn to China.[130] This leaves the DoD with limited supply sources (i.e., China) for microchips and equipment.

Additionally, China could further disrupt supply chain as they are a hostile threat to suppliers and other manufactures within the region, such as Taiwan, South Korea, and Malaysia. China continues to challenge Taiwan's independence; escalating concerns regarding TSMCs viability.[131] All are in easy range of Chinese missiles, subversion, and air or maritime interference.[132]

Appendix – Section II

Porter's Diamond.



Porter argues that four attributes define a nation's competitiveness in an industry: factor conditions, demand conditions, related and supporting industries, and firm strategy, structure and rivalry (firm conditions).[133] Factor conditions focus on the status of 'factors of production,' such as skilled labor, partnerships, and alliances, necessary to be competitive.[134] Demand conditions assesses domestic demand for the product, while related and supporting industries evaluates whether such industries are present or not in a country. Finally, the firm strategy, structure, and rivalry (firm conditions) interrogates national conditions governing how companies are "created, organized, and managed" as well as the nature of domestic firm rivalry.[135] Taken together, these attributes can encourage, repel, or even maintain a nation's competitiveness. By amplifying strengths or correcting weaknesses in the Diamond, government policy can promote national competitiveness.

Appendix – Section III

Congressional activities

The funding bills can be broadly divided into at least 12 titles.[136] There are four substantial divisions of the bills. Division A funds much of the CHIPS Act's support for American semiconductor production.[137] Division B funds scientific research and development.[138] Divisions D & K prescribe extensive and complex policy requirements – D in foreign policy[139] and K in trade policy.[140] All the bills address a mass of issues beyond the narrow semiconductor industry – broad foreign, trade, environmental policies; Taiwan and Great Power policies; harassment in the workplace, forced labor, remuneration for workers disadvantaged by trade, and a host of other unrelated areas.[141] Any wholistic consideration of the legislation's mobilization effort must understand the many broader requirements it imposes on the government.

The America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science Act of 2022, or COMPETES, divvies out funding over five fiscal years. It provides one-time funding totaling approximately $54 billion to various initiatives supporting the semiconductor industry (Division A).[142] There are a few funds for small projects – $2 billion for the Defense Department to carry out the research, development, test and evaluation, workforce development, and other requirements unique to the intelligence community; $500 million for the State Department to provide for international information and communications technology security and semiconductor supply chains; $1.5 billion in direct appropriations for the Public Wireless Supply Chain Innovation Fund.[143]

But the lion's share of the Division A funding, $50.2 billion, is for the DOC to give federal financial assistance to facilities in the United States that fabricate, assemble, test, and package semiconductors and support semiconductor research and development.[144] Eligible companies must have a demonstrated ability to finance, construct, expand, or modernize a relevant facility.

COMPETES includes subsidies to companies producing the materials used to make semiconductors and semiconductor manufacturing equipment, which USICA does not.[145]

CHIPS present several challenges to mobilizing to rebuild the American semiconductor industry. One drawback is that the appropriation is "one and done." While the funding is massive and spread out over several years, it is not recurring or sustained. This contrasts with Taiwanese, South Korean, and even Chinese approach of making more use of ongoing incentives such as tax credits and reductions.[146] Tax incentives avoid picking winners and losers, a key concern for any subsidy regime (see below). Tax credits were proposed in 2021 legislation, Facilitating American Built Semiconductors (FABS), but stalled in committee.[147] Supporters still hope to leverage Build Back Better investment credits, but that is far from certain and outside the scope of CHIPS.[148]

Having the government pick winners and losers is a challenge of its own. It is impossible to forget the last time the state underwrote cutting-edge companies with great fanfare. It was a public relations disaster and far from successful, to say the least. The government famously provided loan guarantees totaling around $2.5 billion in 2011 to 19 green energy companies that went bankrupt.[149] One of these, Solyndra, drew the most notoriety, but it was not even the largest.[150] The whole affair convincingly demonstrates that Commerce and other federal entities are hardly capable capital investors. With an exponentially larger pot of money, CHIPS will be far riskier and more complex. There is a real danger of propping up failing companies, or the wrong ones, and replicating 2011 on a grand scale.

CHIPS also risks generating oversupply in chip manufacturing. Many countries, not just the U.S, are flooding the market with incentives (subsidies, tax breaks, etc.) to build fabs. At the same time, fab building projects are awash in private investment capital. These facilities will take years to construct and will reach full production around the same time. While some analysts remain optimistic that the growth in demand will keep up with the surge in supply, others are less optimistic.[151] The expansion of semiconductor plants will also contort the labor markets, with massive demand chasing limited supply.

Given the many significant risks of massive subsidies distorting mid-term semiconductor markets, mobilizing and deploying Division A funding will demand great care and planning. The legislation does provide some guard rails, limiting subsidies to established and stable companies.[152] However, Division A funding is extremely front-loaded, with 46% of the funding allocated to fiscal year 2022.[153] This is a huge problem since it rushes mobilization and almost guarantees failure. Given the huge sums involved, surge and mobilization on every level should be deliberate.

Given DOC lead role in running the program and its limited capacity, it should first focus on quickly building its capability, using other federal agencies to help. DOC had a tiny discretionary budget of $9 billion in 2021; it is hardly equipped to manage five times that amount.[154] An arrangement for support with DoD, accustomed to managing such huge sums, may help. But DoD's expertise lies in large weapons procurement projects, not semiconductor fabrication.

DOC should take all the time it needs to build a competent cadre of semiconductor investment experts, seeking time extensions from Congress as required. It should develop the internal expertise required before giving away a single dime. The political and economic pressure to rush funds to market will be difficult to resist, and the project will risk failure. But whatever disadvantage delays cause, they pale in comparison to the disarray of throwing billions away due to incompetence and incapacity. DOC should meticulously structure the subsidies conditionally, providing graduated funding linked to metrics and proven success and avoiding lump-sum payouts.

The legislation's Divisions B authorizes a total of $148 billion.[155] It drastically increases Research & Innovation budgets of federal agencies involved in research, including the Department of Energy, NIST, and the National Science Foundation (NSF).[156] NSF's budget doubles in six years, for example.[157] While the industry consensus is that research needs government assistance, these resources mostly directed outside the semiconductor industry. These increased resources address a range of perceived U.S. research shortcomings. In addition, doubts linger about NIST and NSF in generating productive research outcomes.

The other leading divisions (D & K) are less awash in money, but still authorize $43 billion.[158] They primarily develop much-needed policy improvements but also present mobilization problems. K begins to address some of the systemic problems causing the migration of manufacturing offshore.[159] However, both often apply broadly, well beyond semiconductors. For example, Division D provides State support to companies facing Chinese supply chain problems[160] and bolsters a program to counter China's Belt and Road initiative, though with paltry sums.[161] USICA directs DOS to compile and publish a couple "naughty lists." One is an IP Violators list of entities (including corporate officers and shareholders) benefitting from the theft or coercion of American technology.[162] Another list summarizes Chinese entities benefiting from Chinese subsidies and favorable treatment.[163] However, the legislation provides no basis for using the lists.

From a mobilization perspective Division D imposes significant new reporting and actions on the DOS. As a small agency, it is questionable whether it has the capacity to meet these many demands. While D does require a plan for beefing up DOS Indo-Pacific staffing and provides $3.2 billion in foreign assistance and diplomatic engagement for the region, the increased workload hits years before the resources can be applied.[164,165] So effective mobilization here will also demand substantial extensions to ensure time to surge up for effective policy and research. Most of its provisions have little to do with semiconductors, or apply to all industries, not just semiconductors.

More than the rest of the CHIPS Act, Division K has some encouraging strategic policy improvements, specifically in trade. It streamlines and strengthens anti-dumping efforts, including currency manipulation.[166] It blocks duty-free treatment for goods from non-market economies on the USTR watch list.[167] It establishes a process to block the offshoring of critical capabilities to adversaries.[168] More than most other CHIPS provisions, it relates directly to the semiconductor industry. However, mobilization here remains difficult since it imposes heavy reporting and enforcement activities on the tiny USTR and the already overburdened DOC. Properly implemented, its provisions will some legitimate effect on leveling the lopsided field in trade, particularly with China, so are vital. A surge in capacity and additional implementation time is essential to ensure they are impactful.

Appendix – Section IV

Additional actions for Allies and Partners

- Enhance cooperation to identify existing and potential supply-chain risks – particularly in the context of strategic dependence on China. This should involve mapping the key players, collecting, and sharing information to prevent issues at choke point in critical supply chains.

- Develop strategies for joint stockpiles or strategic reserves of essential goods to create the required buffers. For example, stockpiling medical supplies would be hugely important to address future pandemics.

- Secure supply chains inside NATO with countries like Canada which has a vast number of raw materials and rare earth minerals. Such cooperation will be vital for the U.S. and the EU in light of China's dominance in this area. One method could be to provide financial support (i.e., in the form of subsidized storage) to encourage firms in a partner country to hold larger inventories of rare-earth elements. Another method could be the establishment of national stockpiles which are shared, and for which stress tests are developed.

- Promote extended cooperation with U.S partners like Australia, South Korea, Japan, and Taiwan. This outreach would magnify the efficiency of the effort. The U.S. could join the trilateral SCRI (Supply Chain Resilience Initiative) established in April 2021 by Australia, India, and Japan, both to strengthen supply-chain resilience and to align the SCRI more closely in the future.

- Expand their trade agreements with third countries which could help diversify markets and reduce dependencies. The U.S. and EU need also to modernize their export regulation by removing tariff and non-tariff barriers. As each other's most important trading partners, all relevant parties should also revisit and intensify efforts for bilateral U.S.–EU trade deals.

- Cooperate in technology, to strengthen digital supply-chain security. A first approach has been made with the creation of the Trade and Technology Council (TTC) between the EU and the U.S., launched in April 2021. The TTC was borne out of growing recognition on both sides of the Atlantic that the challenges and opportunities of digitalization cannot be tackled alone—from next-generation networks and semiconductors to data privacy and digital monopolies.[169]

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1. There is no definitive formula for a wicked problem.
2. Wicked problems have no stopping rule, as in there's no way to know your solution is final.
3. Solutions to wicked problems are not true-or-false; they can only be good-or-bad.
4. There is no immediate test of a solution to a wicked problem.
5. Every solution to a wicked problem is a "one-shot operation"; because there is no opportunity to learn by trial-and-error, every attempt counts significantly.
6. Wicked problems do not have a set number of potential solutions.
7. Every wicked problem is essentially unique.
8. Every wicked problem can be considered a symptom of another problem.
9. There is always more than one explanation for a wicked problem because the explanations vary greatly depending on the individual perspective.
10. Planners/designers have no right to be wrong and must be fully responsible for their actions.

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