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Cross-Network Weaponization in the Semiconductor Supply Chain

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How do states' positions across multiple and interconnected economic networks affect their power? The Weaponized Interdependence (WI) scholarship emphasizes that states centrally located in global economic networks have access to new sources of coercion. In this paper, we look at how their positions across multiple networks interact with each other to create new opportunities and vulnerabilities. We use network analysis to map the semiconductor supply chain and show that it can be viewed as four interrelated networks: (1) design, (2) raw material, (3) manufacturing equipment, and (4) assembled chips. We then highlight how states' centrality varies across these networks and how it shapes their respective opportunities for coercion. Looking specifically at the United States, we emphasize how its centrality in the design network enables it to weaponize chokepoints in the trade network of assembled chips. In so doing the paper makes three contributions. First, it highlights how interactions among multiple economic networks provide new opportunities for states to weaponize interdependence. Second, it contributes to recent attempts using network analysis to analyze structural power on the global stage. Last, it demonstrates how network methodology can help detect *potential* (ab)uses of WI and how the potential for weaponization evolves over time.

¿Cómo afectan a su poder las posiciones de los Estados a lo largo de redes económicas múltiples e interconectadas? El estudio de la Interdependencia Armada (WI, por sus siglas en inglés) enfatiza que los Estados ubicados en el centro de las redes económicas globales tienen acceso a nuevas fuentes de coerción. En este artículo, analizamos cómo sus posiciones en múltiples redes interactúan entre sí para crear nuevas oportunidades y vulnerabilidades. Utilizamos el análisis de redes para mapear la cadena de suministro de semiconductores y demostrar que esta se puede ver en forma de cuatro redes interrelacionadas: (1) diseño, (2) materia prima, (3) equipos de fabricación y (4) chips ensamblados. A continuación, destacamos cómo la centralidad de los Estados varía a través de estas redes y cómo da forma a sus respectivas oportunidades de coerción. Si nos fijamos específicamente en el caso de los Estados Unidos, hacemos hincapié en cómo su centralidad dentro de la red de diseño permite a los Estados Unidos convertir en un arma los embotellamientos que se producen dentro de la red comercial de chips ensamblados. De este modo, el artículo hace tres contribuciones. En primer lugar, destaca cómo las interacciones entre las múltiples redes económicas ofrecen nuevas oportunidades para que los Estados utilicen la interdependencia como arma. En segundo lugar, contribuye a los intentos recientes de utilizar el análisis de redes para analizar el poder estructural dentro del escenario global. Por último, se demuestra cómo la metodología de redes puede ayudar a detectar posibles (ab)usos de la WI y a comprender su evolución futura.

Comment la position des États au sein de multiples réseaux économiques interdépendants affecte-t-elle leur pouvoir sur la scène internationale ? La recherche sur l'interdépendance arsenalisée (WI, acronyme en anglais) souligne que les États détenant une position centrale au sein de l'économie mondiale ont accès à de nouveaux outils de coercition. Dans cet article, nous démontrons comment leurs positions à travers divers réseaux interagissent et créent de nouvelles opportunités ou vulnérabilités en matière de coercition économique. À l'aide d'une analyse de réseaux, nous soulignons que la chaîne d'approvisionnement en semi-conducteurs peut s'envisager comme quatre réseaux interdépendants : (1) conception; (2) matières premières; (3) équipements de production; et (4) puces assemblées. Nous montrons ensuite comment la variation de la centralité des États dans chacun de ces réseaux façonne leurs opportunités de coercition respectives. En nous attardant au cas des États-Unis, nous démontrons que leur centralité dans le réseau de conception leur permet d'activer à des fins coercitives les goulets d'étranglement dans le réseau commercial de puces assemblées. Ce faisant, l'article apporte trois contributions à la littérature en relations internationales. Il souligne tout d'abord que les interactions entre plusieurs réseaux économiques créent de nouvelles voies de coercition pour les États dans un contexte d'interdépendance arsenalisée. Ensuite, il contribue aux tentatives récentes d'utiliser l'analyse de réseaux pour examiner la puissance structurelle sur la scène internationale. Enfin, il démontre comment l'analyse de réseaux comme méthodologie peut permettre de détecter les potentiels abus de l'interdépendance arsenalisée et de mieux comprendre son évolution future.

Introduction

Semiconductors have become central to global geopolitical struggles. As political tensions emerge along the highly globalized semiconductor supply chain, namely between China

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and the United States (U.S.) and its allies in Asia and Europe, countries have sought to secure their access to this critical dual-use technology (Miller 2022). These efforts have taken two forms. First, from the European Union to the U.S. to China, the great economic powers are investing heavily in securing their share of global semiconductor manufacturing and localizing more of the production process. Second, semiconductors have also become a significant tool of Weaponized Interdependence (WI)—chiefly by the U.S. Under the Trump Administration, Chinese technology giant Huawei was targeted with sanctions, cutting off its access to advanced semiconductors that China is unable to manufacture itself. In February 2022, the U.S. also restricted Russia's access to semiconductors in an effort to hamper its war efforts in Ukraine (Detsch and Gramer 2022). According to some reports, Russia has been forced to repurpose semiconductors from dishwashers and refrigerators for use in its military equipment (e.g., Whalen 2022). Most significantly, however, was the initiative launched by the Biden Administration in October 2022 to block China's entire technology sector from accessing U.S.-made equipment, software, and components used in the production of semiconductors, as well as advanced chips needed for artificial intelligence and supercomputing (Allen 2022).

As will be discussed in this article, the weaponization of semiconductors has been successful for the U.S., despite accounting for just thirteen percent of assembled semiconductors trade globally in 2019.[1] To understand how the U.S. was able to successfully restrict access to semiconductors despite its modest share of the international market, we argue that we need to unpack the multiple interrelated networks forming the semiconductors' supply chain. Our analysis builds on the recent WI literature, which emphasizes the role of global economic networks in power dynamics among states (Drezner, Farrell, and Newman 2021; Farrell and Newman 2019a). WI argues that centralization tendencies in networks create new opportunities for coercion. More than simply leveraging asymmetrical relations in bilateral relations (Keohane and Nye 1977) through market access decisions (Tusikov 2019; Gray 2021), states exploit their structural position in the global economy to coerce others.

One of the key arguments of the WI literature thus far is that states can weaponize networks in which they hold a central position. In their original contribution, Farrell and Newman (2019a) look at the inter-bank global communication system and the Internet as two networks that the U.S. and, to some extent, the European Union could weaponize because of their control over central hubs in both. However, industries or economic sectors are rarely made of one single network. For example, the Internet combines multiple networks. The submarine cables that support international data flow are, for example, distinct from the network of online services provided by companies such as Google or Amazon. Importantly, each of these—and other networks that make up the "network of networks" that is the Internet—have their own topography.

By examining the semiconductor industry, we argue that WI must analyze both the multiple networks that make up an industry or market, and how interaction between these networks affects their weaponization. The paper divides the semiconductors' supply chain into four interconnected networks: (1) design, (2) materials, (3) production equipment, and (4) assembled chips. Using network analysis, we map each network's topography and show that countries' positions across these four networks differ significantly. We chiefly highlight that the U.S.'s position is marginal in all but the design network. We then discuss how its centrality in this network allowed it to weaponize the trade network of assembled chips.

In doing so, we make three contributions. First, we demonstrate the importance of what we call "cross-network weaponization," which explains how centrality in one network can provide leverage in another. Second, we highlight how the U.S.'s ability for cross-network weaponization reflects its structural power in the semiconductor industry. Through its dominance over the most knowledge-intensive aspects of production, the U.S. not only controls who can access critical information and knowledge, but also semiconductors manufacturing. This analysis shows that market share data in the production of semiconductors alone underplays the U.S.'s influence over the industry, with implications for current initiatives in the U.S. and Europe to increase their respective market share. Third, we offer one of the first applications of network analysis in the study of WI. Even though network ideas are at the heart of the WI literature, network analysis has not been broadly used in its study. We show how network analysis can help identify opportunities and vulnerabilities by producing network statistics.

The remainder of this paper is divided into five sections. The first reviews the literature on WI and details under which conditions states can weaponize economic relations across multiple networks. The second presents the case of semiconductors. The third details our methodology and discusses the topography of each network forming the semiconductor supply chain. The fourth probes our argument by comparing two recent cases of weaponization of the semiconductor supply chain by Japan and the U.S. The fifth finally discusses what our findings mean for the structural power of the U.S.

WI across Networks

The weaponization of asymmetric economic relationships is not new in either theory or practice. In an early contribution to the modern field of international political economy, Albert Hirschman (1945) famously detailed how Nazi Germany coerced other countries through bilateral asymmetries. Meanwhile, Robert Keohane and Joseph Nye (1977) theorized that asymmetrical interdependence was a key source of power in a global economy. Since then, an extensive scholarship on economic sanctions has analyzed how states use such asymmetries to coerce more dependent trading partners (Bapat and Morgan 2009; Pape 1997; Drezner 1999). The main contribution of WI to these debates is its analysis of network structures, as opposed to dyadic relationships. It highlights how states with authority over central nodes in hierarchical networks can leverage them to coerce others. Hierarchical networks are structured around one or a few nodes (i.e., actors or institutions) with a high centrality (Oatley et al. 2013, 137). In contrast to bilateral dependencies, there are generally few exit or substitution options for entire networks (Drezner 2021, 8). States controlling highly centralized networks thus have more leeway to exert their influence, above and beyond the bilateral asymmetries they may enjoy with the target state.

Similarly, a growing literature on global infrastructures emphasizes how the entanglements of economic actors, institutions, and technologies create new sources of power (Weiss and Thurbon 2018; Bernard and Campbell-Verduyn 2019; Braun 2020; Westermeier 2023; Petry 2023). Looking primarily at finance, it analyzes how state and non-state actors who control key "conduits" for financial activ-

[1] Authors' calculus, see figure 3.

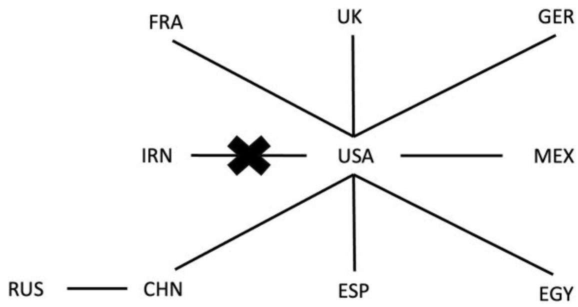

Figure 1. Chokepoint effect

ity (Braun 2020, 400) or enable the "connectivity" of financial actors (Petry 2023, 320)—through, for example, repo markets, payment systems or financial exchanges—can use their position to advance their interests. Despite their different academic origins, with WI building on network theories and infrastructural research on socio-technical studies, both strands of literature emphasize the architectural aspect of power. They point out that more than merely using material or ideational resources, economic actors can leverage their position relative to others to advance their interests. This form of power can take many forms, including penalizing or excluding others from accessing the benefits of global economic networks or infrastructures.

Farrell and Newman refer to this as the chokepoint effect (2019a).[2] One example is the U.S.'s weaponization of the dollar through financial sanctions. Given its network prominence, losing access to the dollar can severely limit a state's, company's, or bank's access to global markets, even when their financial ties with the U.S. are limited (Drezner 2015; Zoffer 2019). As such, more than individual countries, the entire network is dependent on the U.S. dollar, and thus it can be used for coercive purposes, even in trade between two independent parties. As seen in the case of the Iranian sanctions, the U.S.'s decision to withdraw from the 2015 nuclear deal impeded the ability of the European Union to maintain its part of the agreement with Iran. Figure 1 depicts the chokepoint effect in a simplified network. It shows almost all countries connected to the U.S. as they primarily rely on its dollar to settle international transactions. By limiting Iran's access to its currency, the U.S. impeded it from transacting with most other countries in the global economy. More than ending their bilateral relationship with Iran, it excluded it from the entire network.

Significantly, as de Goede and Westermeier argue, infrastructures are not merely passive sites of economic activity that actors can temporarily weaponize (2022, 2). They are themselves expressions of continuous power conflicts. If the original WI argument tended to take network structures as given (Gjesvik 2022, 723), Drezner, Farrell, and Newman (2021, 313) also recognized that they are dynamic. Once states weaponize chokepoints, both companies and states make decisions that will alter the structure of economic networks and thus the potential effect of its weaponization and potential use in the future. Network approaches can help make sense of this process by providing a conceptual toolkit and methodology to investigate how economic structures evolve over time.

Furthermore, while states cannot control how other actors will respond to weaponization, they nevertheless may intentionally seek to initiate change in network structures. Indeed, restructuring networks can itself be a strategy of WI. Forcing other actors to reroute their activities can further entrench a weaponizing state's position and control over global economic networks or infrastructures. The exclusion of some countries from strategic networks, including those involved in the production of dual-use technologies, has been a longstanding strategy of the U.S. (Klaus 2003).

In this paper, we argue that this can occur through the weaponization of chokepoints across multiple networks. As the wide variety of networks investigated in the early WI literature (e.g., trade, finance, energy, Internet, etc.) demonstrates, the global economy is not made of one but multiple networks. Up to now, these networks have tended to be analyzed separately. In one of the only contributions in the early WI literature specifically distinguishing multiple economic networks, Meierding (2021, 169) demonstrates how the market for oil and gas incorporates three separate networks: energy trade (sales of oil and gas), transportation (via sea or pipeline), and financial exchange (for payment and insurance). While, according to her analysis, the U.S. does not dominate, and thus has limited capacity to weaponize, the energy trade network, its naval dominance affords it some capacity to weaponize the transportation network. However, it is the U.S.'s hegemonic status in the financial exchange market that affords it the power to weaponize the energy market most effectively. Therefore, to measure only sales in the energy market, as did the U.S.'s own 2017 National Security Strategy, fails to appreciate where the power to weaponize the industry truly lies. Similarly, Kardon and Leutert (2022) highlight that China relies on a growing network of civil ports to make up for its minimal overseas network and project its power.

As states find themselves in a marginal position in some networks, these two studies show that they can attempt to improve their situation in other networks. As Farrell and Newman have noted, "only those states that have physical or legal jurisdiction over [central] nodes will be able to exploit the benefits of weaponized interdependence" (2019a, 56). Having authority over the central node in a hierarchical network is, therefore, one of two necessary conditions for states to weaponize interdependence, with the other being a state's regulatory capacity to activate the chokepoint. Without such control, states must instead work cooperatively and through diplomacy to achieve their aims (Raustiala 2002; Slaughter 2004). Considering its marginal position in the energy trade network, the U.S., for example, cannot weaponize it alone. The only way it could do so is "multilaterally, by persuading other countries to join it in sanctioning or embargoing a targeted state" (Meierding 2021, 174).

The difficulty in building and maintaining such a coalition is one reason states may look at other networks to assert their influence. By using its dominance in the energy financial transaction network, the U.S. can attempt to *de facto* lock out a targeted state from the energy trade network. The weaponization of both economic networks, however, is not functionally equivalent. A country targeted by U.S. financial sanctions can work toward de-dollarizing its energy transactions and still be part of the energy trade network. It is chiefly what Russia and Venezuela have attempted to do in recent years to different degrees of success (McDowell 2021). In addition to special financial vehicles allowing trade through barter-like mechanisms, these initiatives could "fracture the financial infrastructure centered around the U.S. and, over time, limit its leverage in energy payments" (de Goede and Westermeier 2022).

Different networks can also interact in productive ways. Cross-network effects have recently been studied in inter-

[2]On the concept of chokepoint, see also Tusikov 2017.

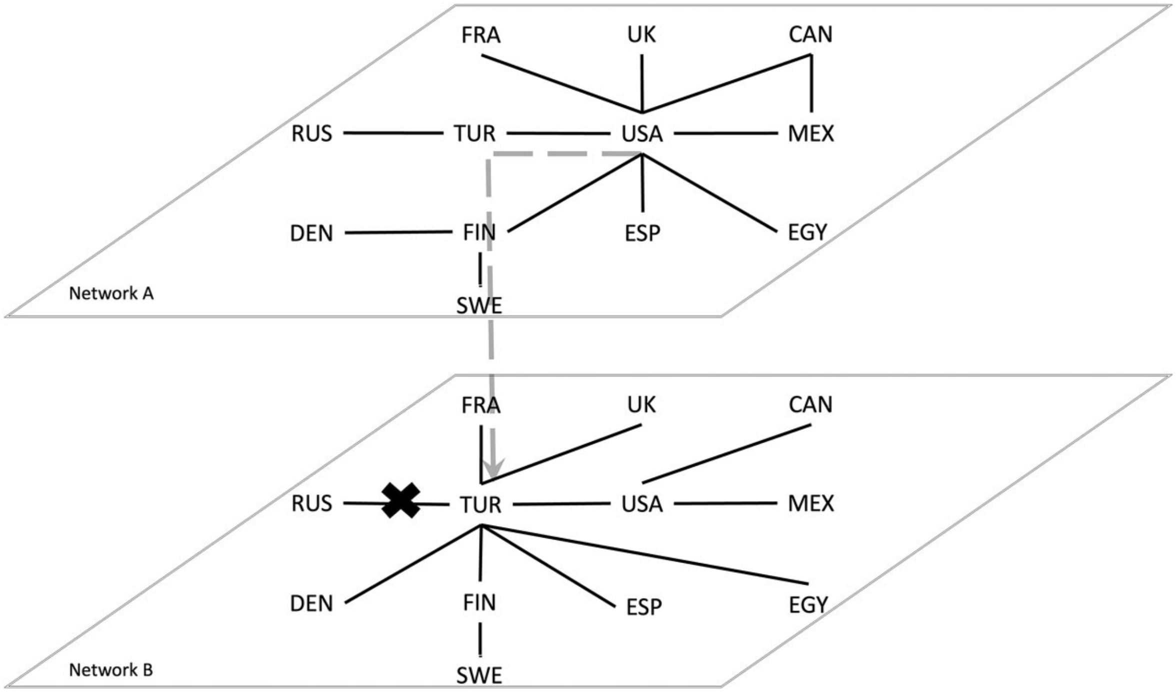

Figure 2. Cross-network weaponization of chokepoints

national relations to examine the evolution of institutional landscapes (Milewicz et al. 2016; Htwe et al. 2020; Kinne and Bunte 2020). Together these studies show how the structure of one network can shape another. Countries that sign bilateral investment treaties are, for example, more likely to sign regional trade agreements together (Htwe et al. 2020). Similarly, the signature of tax treaties among countries shapes the network of bilateral investment flows across countries (Thrall 2021).

We argue that another cross-network effect can be the use of a chokepoint in one network through the control of a chokepoint in another. In addition to shaping their respective structure, interactions among networks can offer new pathways to weaponize chokepoints. Instead of directly controlling the chokepoint in one network, a country can threaten to exclude or penalize the dominant state in one network through its control of a chokepoint in another, as shown graphically in figure 2. In network A, the U.S. has control over the central hub. However, it does not have a direct link with Russia and cannot use its position to coerce it. In network B, the U.S. is not the most central actor and cannot reap the benefits of WI. By threatening Turkey to exclude or penalize it in network A, the U.S. can force it to weaponize its position toward Russia in network B.

An example of cross-network weaponization is the recent proposal by the U.S. and its allies to penalize Russia's oil exports following the invasion of Ukraine. After attempts at limiting their imports of Russian oil had limited effects due to Russia's own centrality in the energy trade network and capacity to find other export markets, these countries planned to implement a cap price on Russia's oil export. To do so, they would limit "the availability of shipping and insurance services that enable the worldwide transport of Russian oil" (Chazan, Fleming, and Sheppard 2022). Without control over the central node in the trade energy network, the U.S., and its allies, in effect, threatened to weaponize their control over two other networks to force other importers of Russian oil to align with them and apply a cap price.

Cross-network weaponization is a function of the same two conditions from the original framework of Farrell and Newman (2019a, 56): network topography and a country's institutional capacity. However, slight adaptations are made to both. First, the topography of not only one, but two networks must be sufficiently centralized to allow for weaponization. More specifically, a country controlling a central hub in one economic network must be connected to one or a few countries that have authority over a hub in another. As noted above, a country controlling a hub in one network can help create one in a second network by forcing countries in it to act jointly. However, these countries must together form an economic hub that others cannot easily circumvent. While economic networks are constantly evolving, notably based on business decisions taken by private companies, states can decide to weaponize a network based on its recognition of its centrality at a specific point in time.[3] Significantly, while we take the network structure as given before its weaponization, we also acknowledge that they are not static. As previously mentioned, states may weaponize a network with the aim of shaping its long-term structure and exerting structural power in the global economy. We discuss this point at greater length in the last section.

Second, states planning to weaponize chokepoints across networks must have domestic institutions allowing them to do so. However, more than simply giving them control over one economic hub, their domestic institutions must enable them to create linkages between hubs in different networks. It is not enough to have the capacity to limit access to their markets or establish export controls. A country must also be

[3]The question of how easily other states or private actors can change a network structure to escape its weaponization, or in other terms, to what extent a network structure is stable over time, is an important one to better understand the potential short- and long-term effects of WI, which is however not the focus of this study.

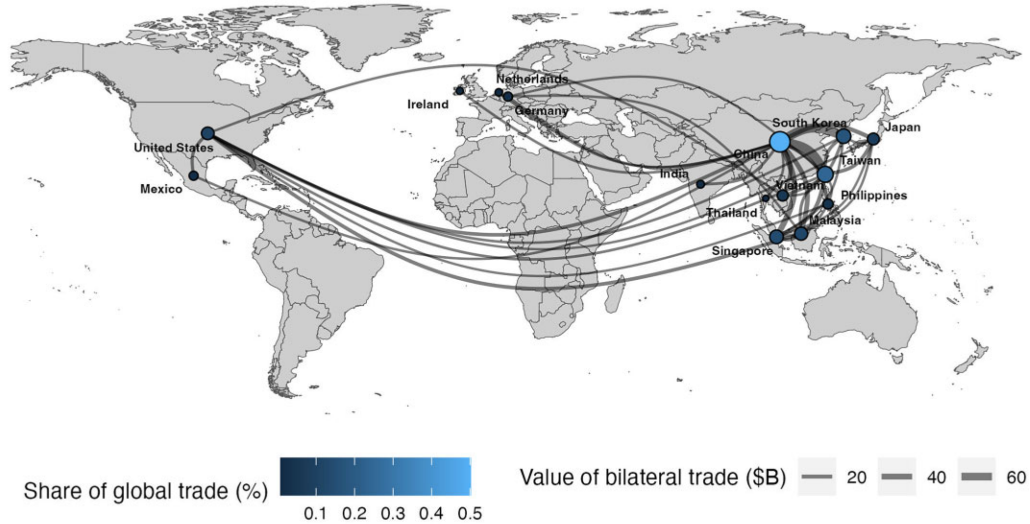

Figure 3. Map of global trade in assembled semiconductors (HS 8541 and HS 8542) in 2019.

able to link these decisions to the ones made by actors in other economic networks. It implies an extraterritorial application of rules, which the U.S., for example, does through secondary sanctions penalizing companies in foreign countries that do not abide by its rules (Kittrie 2009; Norrlof et al. 2020; Whyte 2022).

In the following sections, we progress this argument by looking at the case of semiconductors. We first show that the semiconductor supply chain is not one but multiple interrelated networks. We highlight that even in one industry, there can be multiple pathways to weaponize interdependence.

Networks in the Semiconductors' Global Supply Chain

Semiconductors, or more colloquially "chips," are essential to the global economy. From cars to computers, anything with some electronic components needs them to operate. Semiconductors are integrated circuits allowing the transfer of electronic information, acting as the "brains" of electronic devices. While they vary in size, the most advanced ones are smaller than 10 nanometers (i.e., a millionth of a millimeter) and are indispensable to developing increasingly powerful yet small electronic devices. These include many consumer goods, such as smartphones and other so-called "smart" devices, as well as military technologies, such as satellites, drones, and missiles.

Since being invented and first manufactured in the U.S., the production of semiconductors has been progressively offshored to reduce costs and benefit from increasing returns. Today, semiconductors are "the world's fourth-most-traded product [by value], only after crude oil, motor vehicles and parts and refined oil" (Varas et al. 2021, 36). While no single country can claim to control its global supply chain, most industry experts argue that its gravity center is now in Southeast Asia. The region is estimated to account for three-quarters of the global manufacturing output of semiconductors (Varas et al. 2021, 33).

Trade flows reflect this change in semiconductor production. Figure 3 presents the trade network of assembled semiconductors in 2019 among fifteen countries, which together represent 98 percent of all global trade value in semiconductors.[4] Nodes represent countries and ties trade flows representing at least 0.5 percent of semiconductors' global trade. The size of each tie represents the total value (imports + exports) of bilateral trade, and the size and color of each node their share of the global trade in semiconductors.

Out of the 15 countries included in figure 3, two are in America, three in Europe and ten in Asia. The U.S. and European countries seemingly hold a more marginal position. To be sure, drawing this network on a world map artificially presents the U.S. as distant from the network's core. It is still a relatively central actor in the semiconductor trade network, accounting for thirteen percent of all global trade in semiconductors, and the fourth-most well-connected country after China, Taiwan, and South Korea in figure 3. Nevertheless, it has only a fraction of China's (53 percent) or the ten Asian countries in figure 3's (90 percent) global trade shares.[5] Moreover, the U.S.'s position is marginal in the production of the most advanced semiconductors, with Taiwan and South Korea being home to the two global leaders: Taiwan Semiconductor Manufacturing Company and Samsung.

However, focusing on the production network only offers a partial picture of the semiconductor global supply chain. Before semiconductors can be manufactured and assembled in other electronic devices, many additional economic activities must take place. Understanding the potential vulnerabilities and opportunities in the semiconductor supply chain requires paying attention to all the parts of their production. While Southeast Asia is a key region in the trade network of semiconductors, this is mostly in the trade of assembled chips. However, semiconductor production is notoriously complex and occurs in one of the most globalized supply chains of any product, which data on the trade of assembled semiconductors alone fails to highlight.

[4]This network is made using the International Trade Database at the Product-level, or BACI database (French acronym), providing trade data at the product level (Gaulier and Zignago 2010) and aggregating data for products classified under Harmonized System (HS) codes 8541 and 8542 (Bown 2020).

[5]The sum of the U.S. and Asian countries' global trade share is higher than 100 percent since the calculus of their respective share includes the trade value of their exchanges with each other. Summing up their share would thus lead to counting the value of their trade between them twice.

Table 1. List of networks and data sources

Supply chain activity	*Network*	*Data*
Design	Network of patent citation	National citations in CPC H10L patent filing from the OECD triadic patent database
Materials	Network of trade in silicon	Sum of bilateral trade value in HS 280641 and HS 280649
	Network of trade in hydrogen fluoride	Sum of bilateral trade value in HS 281111
Production equipment	Network of trade in semiconductor production equipment	Sum of bilateral trade value in HS 381800, HS 848610, HS 848640, HS 903082, and HS 903141
Assembled semiconductors and integrated circuits	Network of trade in semiconductors	Sum of bilateral trade value in HS 8541 and HS 8542

The semiconductor supply chain has three distinct phases of production. The first phase, design, includes software and intellectual property used for manufacturing purposes. It is the most heavily knowledge-intensive stage and accounts for approximately half of both the industry's research and development (R&D) expenditure and its added value (Varas et al. 2021). The second phase is "front-end" fabrication, which involves highly advanced processes that print integrated circuits onto silicon wafers. It is also a knowledge-intensive stage that accounts for 13 percent of the industry's R&D and 24 percent of its added value. The last phase, the assembly or "back-end" manufacturing is the most labor-intensive part of the manufacturing process, accounting for just 3 percent of R&D and 6 percent of its added value (Rho et al 2015; Varas et al. 2021).

Each phase of semiconductor production has a different geography. While China enjoys a large market share in back-end semiconductor manufacturing, the U.S., Europe, South Korea, and Japan dominates design. Front-end manufacturing is more evenly split between China, the U.S., South Korea, Japan, and Taiwan, with Europe also having a sizable presence (Varas et al. 2021). Therefore, at first glance, no one country dominates all three phases of the semiconductor's production, and further analysis is required to identify hierarchical networks. For this, we disaggregate the semiconductor supply chain into four networks: (1) design, (2) materials, (3) production equipment, and (4) assembled chips. Each layer represents a different part of the supply chain. While interconnected and all essential to produce semiconductors, they are distinct networks. They involve different sets of companies exchanging varying resources. Disaggregating the semiconductor supply chain in this way makes it possible to examine how economic power is concentrated across these multi-layered networks so that we can identify where and how cross-network weaponization can occur.

In their work on the governance of value chains, Gereffi, Humphrey, and Sturgeon (2005) distinguish five different value chain structures based on firms' relationships. They chiefly consider how firms involved at all steps of the production process connect to each other to distinguish different governance models. Looking at states' ability to weaponize production hubs located in their territory, we separate the semiconductor supply chain across different networks. This analysis demonstrates that while suppliers in one country may have a dependent relationship with buyers in another, such as in a fully vertically integrated value chain, they may still together represent a chokepoint if no other countries have similar production capacity over which it has authority. The focus on production networks, rather than wealth chains (Seabrooke and Wigan 2017), also reflects the fact that even production hubs creating little added value can be a source of power if sufficiently centralized. For example, states with authoritative control over production hubs of raw materials may be able to pressure other actors, even though it generates less wealth than other more advanced production processes.

The semiconductor supply chain could be further disaggregated to include other important activities, such as the manufacturing of mining tools to obtain raw materials, the construction of the infrastructure necessary to transport these raw materials, or the R&D activities to manufacture the production equipment for semiconductors. These few examples highlight the wide variety of tasks and companies involved in developing highly advanced products like semiconductors, which can all create their own vulnerabilities for individual countries and the global economy. As the COVID pandemic revealed, a failure in the production or transport of one component in a complex supply chain can create significant disruption (McNamara and Newman 2020). For the sake of simplicity and avoiding the risks of decomposing evermore interconnected supply chains, we limit ourselves to the main economic activities associated with manufacturing semiconductors.

To map these respective networks, we use two different sources of data, as summarized in table 1. First, we collected data on trade flows in 2019 for the networks on materials[6], EUV and wafer fabrication equipment, and assembled semiconductors. Using the International Trade Database at the Product-level (Gaulier and Zignago 2010), we aggregate the 2019 trade value in import and export for all Harmonized System (HS) codes associated with these three categories of goods by country pairs (i.e., dyads). We use HS codes at the six-level digit when possible.

Second, we use data on patent citations globally for the semiconductor design network. As opposed to trade in goods, exports of designs or software are more challenging to observe. Trade statistics are either too broad or too incomplete to provide a clear picture (Khan 2020, 17). We use patent citation data as a proxy to identify where most intellectual property related to semiconductors originates and on which countries do they rely to innovate. Significantly, not all patents are of equal quality. In effect, there can be a

[6]We focus on two materials: silicon and hydrogen fluoride. Silicon is by far the main metal used to produce wafers and hydrogen fluoride is one of the prime wet chemicals used in the cleaning and etching process (Khan, Mann, and Peterson 2021; Varas et al. 2021). Both materials moreover have HS codes at the six-digit level allowing us to observe their respective trade networks as opposed to other materials, such as fluorinated polyimide and photoresists, that fall in broader HS categories.

business interest in filing as many as possible to limit competition and create economic rents, posing a risk of overrepresenting the share of knowledge produced in one jurisdiction. Some, for example, note a tendency for over-filing patents in China because of subsidies put in place by the government (Dang and Motohashi 2015). To minimize this risk, we used the Triadic Patent Family Database built by the Organization for Economic Co-operation and Development. It lists patents jointly filed at the European Patent Office (EPO), the United States Patent and Trademark Office (USPTO), and the Japanese Patent Office (JPO). It is broadly considered to identify patents of higher quality as their applicants consider it worthwhile to spend the time and resources to file them in these three key markets. We then computed how many times patents filed by inventors from a given country were cited (inward citation) and how many times they cited patents filed by inventors from other countries (outward citation).

Patents are only one measure of the intellectual property and technical know-how used in semiconductor design. Copyright protects the electronic design automation software used in manufacturing, while tacit knowledge, expertise and trade secrets are also crucial to most production phases. Unlike patents, which are registered with patent offices, the exchange of other forms of intellectual property and know-how is, however, difficult to reliably measure. Therefore, while patent data gives some indication of centrality in design, it remains a partial view. To address this, we supplement the patent data in our analysis below with data on the leading firms in the design of semiconductors.

There are four types of companies involved in semiconductor manufacturing. First, there are so-called *fabless* companies that specialize in design but do not manufacture semiconductors. Instead, these fabless companies outsource production to other companies, known as *foundries*. While foundries specialize in manufacturing, namely "front-end" manufacturing, they have limited to no capacity in design. Third, there are Outsourced Semiconductor Assembly and Test, or *OSATs*. As the name suggests, OSATs conduct testing and assembly, the "backend" manufacturing, for other companies. Last, there are Integrated Device Manufacturers (IDMs)—vertically integrated companies that do design, frontend and backend manufacturing all in-house, though some may outsource select parts of production to foundries or OSATs. We provide data on fabless firms and IDMs, that is companies involved in design, to support our analysis on patents.

Before looking at how these four networks can be weaponized, the next section presents their respective topography. It more specifically highlights where vulnerabilities and opportunities lie for different countries by identifying existing chokepoints.

Chokepoints across the Semiconductor Supply Chain

There is a growing literature applying network analysis to the global political economy—examining centrality in offshore finance (Fichtner 2014; Garcia-Bernardo et al. 2017), corporate ownership (Vitali, Glattfelder, and Battiston 2011; Babic, Fichtner, and Heemskerk 2021), and state capital (Babic, Garcia-Bernardo and Heemskerk 2020; Babic 2023) networks. Moreover, research from Oatley et al. (2013) and Winecoff (2020) uses multi-network analysis to explore political and economic power in the global economy. While all this research provides important insights into geoeconomics, the WI literature has yet to incorporate these insights. In most existing WI research, networks are used as a heuristic tool to describe how WI works rather than as a methodology.

We use network methodology to explain how WI has been used in the semiconductor industry through what we call cross-network weaponization. In doing so we address not only how economic and political power exists within global economic networks, but also how concentration within and across these networks can be and has been mobilized through WI. We more precisely use a measure of strength centrality to identify which countries hold a key position in each network. Strength centrality S_i represents the sum of an actor i's weighted relations x (Opsahl et al. 2010, 246). More formally, it can be given by the following equation:

$$S_i = \sum_{j}^{N} x_{ij},$$

where j represents all other actors and N is the total number of actors in any given network. Directed networks can have a strength centrality measure for inward and outward relations. In a trade network, inward and outward strength centrality respectively equal the sum of a country's imports and exports.

Many popular centrality measures tend to move away from the simple count of relations (weighted or not) and put greater emphasis on an actor's position relative to others (Brandes 2016). Betweenness centrality, for example, calculates the brokerage potential of an actor by looking at the number of times it sits on the shortest path of any given pair of actors. Actors bridging different clusters will have a higher centrality measure even though they might only have a few connections. Eigenvector centrality meanwhile considers the quality of actors' connections. The more central their connections are, the higher their centrality measure will be.

At an aggregate level, betweenness and eigenvector centralities can help detect the existence of chokepoints in the global trade network by highlighting which countries are embedded in global supply chains. A high score on both these measures would indicate that a country tends to trade a lot of intermediary goods with significant trading countries. Using these two measures, Winecoff (2020) shows that the U.S. may in fact remain more central than China in the global trade network even though the latter has surpassed the former in terms of total trade value.

Strength centrality in trade networks for intermediate and final goods separately can yet more directly identify economic concentration in global supply chains. A high strength centrality in outward relations (i.e., exports) highlights a country's control over the production of specific intermediate goods or the assembly of final goods. Meanwhile, high strength centrality for inward relations (i.e., imports) points to a country's reliance on intermediate goods from others in its part of the supply chain. We plot in- and out-strength centrality on an x- and y-axes for each network identified in table 1 to identify both opportunities and vulnerabilities in the semiconductor supply chain.

Design

The U.S. is by far the most central actor in the design or "knowledge" network. Figure 4 shows the strength centrality for the network of patent citations related to semiconductors from 1956 to 2019. Only countries with more than 1000 inward and outward patent citations are labeled for visibility purposes. Again, strength centrality here reflects the

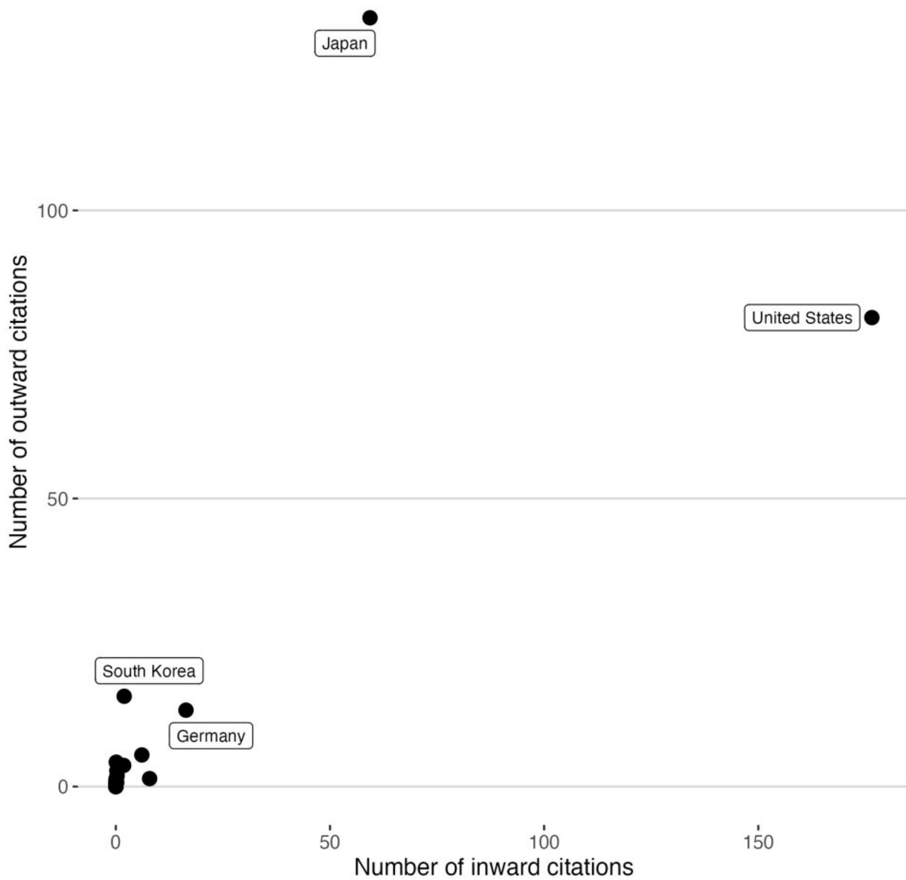

Figure 4. Sum of citations to and from patents (in thousands) (1956–2019)

sum of citations made to and from patents filed by companies in one country. A high strength centrality for inward citations means that patents filed by companies from country X are often used by companies from countries Y, Z, etc. Conversely, a high strength centrality measure for outward citations means that many companies from country X use patents from other countries when developing their own. In other words, many inward citations indicate that a country's technology is often used, and many outward citations reflect a country relying a lot on technologies from other countries.

In this network, the U.S. is by far the country from which patents are the most often cited by companies in other countries. Japanese companies, which filed the most semiconductor-related patents over the years (Hoeren, Guadagno, and Wunsch-Vincent 2015, 12), have almost three times fewer citations. Its higher number of outward citations suggests that many of its companies used American intellectual property in their work. All other countries are clustered in the bottom left of the figure, demonstrating that none have any significant presence in the design of semiconductors. The two minor outliers, South Korean and German companies, which were the other two main patent filers over the last 50 years (Hoeren, Guadagno, and Wunsch-Vincent 2015, 12), can hardly be compared with Japanese and American ones. Meanwhile, China is in the pool of countries in the bottom left corner with a marginal role in the semiconductor patent network. It is partly attributable to the fact that it only started patenting semiconductor technologies in the mid-1990s. Nevertheless, figure 4 shows how big the gap currently is with the U.S. While it is still possible for Chinese or other companies to develop key technologies for the design or production of semiconductors, they will most likely have to rely on technology developed by American companies. As such, the U.S., and to a lesser extent Japan, control a key hub in the design part of the semiconductor supply chain.

Industry reports, moreover, show that the three companies dominating the core intellectual property (reusable modules of chip designs) and electronic design automation software markets, Synopsis, Cadence, and Mentor Graphics, are all based in the U.S. (Khan, Mann, and Peterson 2021, 49). According to Khan, Mann, and Peterson (2021), U.S. companies together own over 95 percent of the global market for electronic design automation software and just over half of the market for core intellectual property. British companies also have a 43 percent share of the latter. More broadly, ten of the top twenty fabless companies and IDMs by revenue in 2019 are headquartered in the U.S., while America's fabless companies and IDMs captured a 50 percent share of all sales across the entire semiconductor industry (Varas et al. 2021). In addition to patent citation data, the domineering presence of American companies measured both by their market share of core intellectual property and electronic design automation software and the market share of American fabless companies and IDMs over industry revenue demonstrates the centrality of the U.S. in the design network.

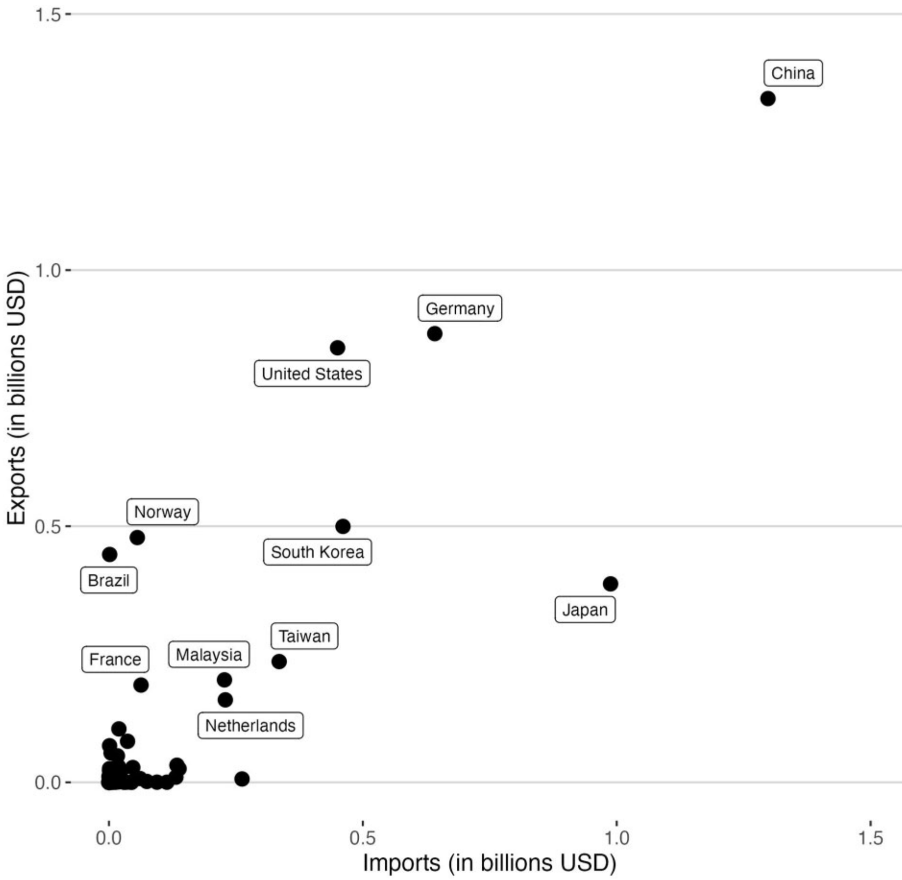

Figure 5. Sum of bilateral trade in silicon (HS 280641 and 280649) in 2019

Materials

Figure 5 shows the strength centrality of countries for the network of trade in silicon, the metal most used in the production of semiconductors. For this figure and the following ones, only countries with a share higher than 0.5 percent of global trade are labeled. Here, China stands out as the most important exporter, which reflects current estimates that it produces 64 percent of all silicon used worldwide and acts as the "breadbasket" of semiconductors' raw materials (Khan, Mann, and Peterson 2021, 52–3). At the same time, China is also, and by far, the most important importer of silicon. Almost all of China's exports are in effect still relatively low-quality silicon, which needs to go through a purification process before electronic circuits can be printed on them. South Korea and Germany are two countries with specialized industries in that process and they together account for 69 percent of all Chinese imports of pure silicon. As such, China is still highly dependent on other countries for its production of silicon. As one of the most common minerals in Earth's crust and with many other countries with a capacity to mine silicon[7], China's lack of domestic purification capacity leaves it in a more vulnerable position than what might appear at first glance.

Hydrogen fluoride is another crucial material used in the cleaning and etching phase of the fabrication of semiconductors to clear the surface of silicon wafers. Figure 6 shows that China has high strength centrality for its exports but—not for its imports. As opposed to silicon, it indicates that China has homegrown capacities to purify hydrogen fluoride before its use in the semiconductor production process. Moreover, 98 percent of Mexico's exports, the second biggest exporter of hydrogen fluoride, go to the U.S., leaving most other countries in the semiconductor supply chain highly dependent on China for hydrogen fluoride. Japan chiefly imports 99 percent of its hydrogen fluoride from China, which it partly refines and then exports back to South Korea.

Production Equipment

In terms of manufacturing equipment, figure 7 shows a reversed image of the material networks. China and Taiwan have a high strength centrality for their imports but not for their exports. Japan, the U.S., and the Netherlands are the three most central exporters. Together, they account for 52 percent of all Chinese imports and 74 percent of Taiwanese imports of semiconductor manufacturing equipment. The picture becomes even starker when looking at production equipment for highly advanced chips. Only two companies, Nikon (Japan) and ASML (Netherlands), produce the lithography equipment to print chips that are smaller than 90 nanometers, and only ASML for those smaller than 5 nanometers (Khan, Mann, and Peterson 2021, footnote 113). The significant value of the Netherlands' exports to

[7]This contrasts with rare earth materials for which China could more effectively apply export controls, but which are not nearly as important as silicon for the semiconductor supply chain (Khan, Mann, and Peterson 2021, 37).

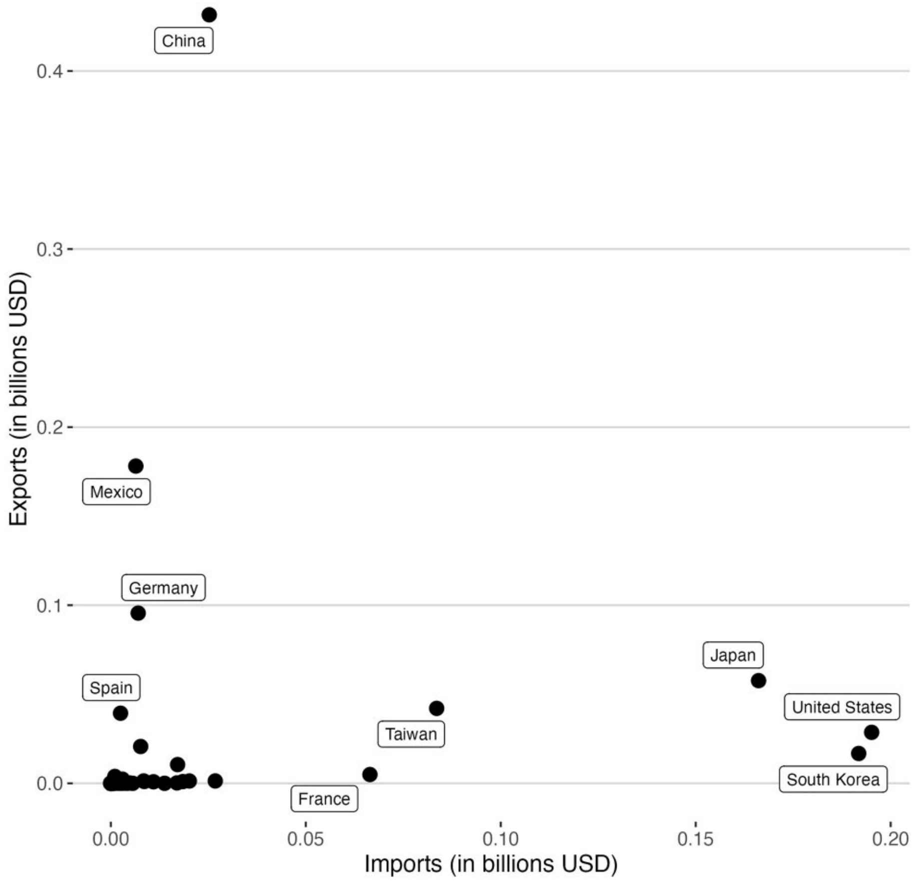

Figure 6. Sum of bilateral trade in hydrogen fluoride (HS 281111) in 2019

Taiwan, which produces almost all these microchips, highlights its greater centrality in the production of these highly specialized equipment. Indeed, the Netherlands account for 28 percent of Taiwan's imports in manufacturing equipment for semiconductors compared to only 7 percent for China.

Assembled Semiconductors

As already highlighted in figure 3, Southeast Asian countries form the core of the trade network of assembled semiconductors. Figure 8 shows that Taiwan and South Korea are, more precisely, the two most important exporters, together accounting for 32 percent of all trade in semiconductors. It reflects their dominance in the production of the most advanced and valuable chips. As previously noted, Taiwan Semiconductor Manufacturing Company is the only company producing chips smaller than 5 nanometers used in most high-end computer processors. China is the third most central exporter as well as the most important importer of semiconductors. In 2019, it imported more than the other five biggest importers of semiconductors combined. Thus, China is most dominant and competitive, not in the production of semiconductors but rather in their assembly and packaging. China imports semiconductors from all around the world to manufacture consumer electronics. Well-known companies such as Apple have offshored the assembly of their products to China. Meanwhile, the U.S. and Japan, the two countries at the center of the design network, rely extensively on other countries to produce and assemble semiconductors. In effect, their companies increasingly follow the "fabless foundry model" by which they design and sell chips but outsource their production to foundries. Their relatively small share of imports tends to indicate that semiconductors are assembled in consumer electronics, chiefly in China, before being exported.

Together, these four networks highlight the existence of multiple potential chokepoints along the semiconductor supply chain. China is a significant player in the materials and assembled chips networks. At the same time, its significant reliance on other countries to purify silicon or produce semiconductors limits its own actual dominance. Meanwhile, the U.S. and Japan are clearly dominant in the design network. The U.S. and Japan also have a significant role in the export of manufacturing equipment, along with South Korea, the Netherlands and Singapore. Finally, Taiwan and South Korea, home to many foundry companies, lead the way in the production of semiconductors, notably the highly advanced ones. In the next section, we discuss how the topography of these different networks provided the U.S. with an opportunity for cross-network weaponization.

Cross-Network Weaponization in the Semiconductor Supply Chain

The above analysis demonstrates that all four networks have unique topographies. Crucially, no single state is central across two or more, let alone all four networks. In the following analysis, we examine how the specific topography of these networks and different states' institutional capaci-

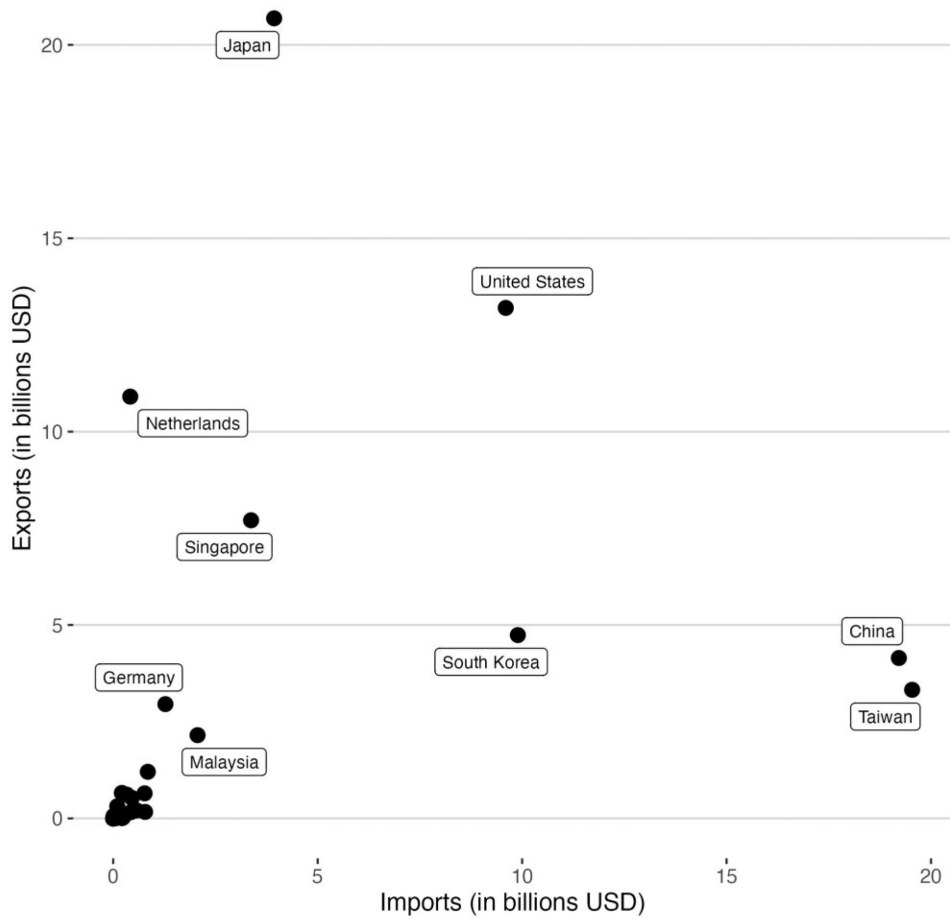

Figure 7. Sum of bilateral trade in semiconductors' production equipment (HS 381800, 848610, 848620, 848640, 903082, and 903141) in 2019 (UN Comtrade data[9])

ties affected the recent cross-network weaponization in the semiconductor supply chain. We consider, first, the Japanese export controls semiconductor components to South Korea over a diplomatic dispute in 2019 and, second, the U.S. export restrictions placed against Huawei in 2020. The Japanese case shows that bilateral asymmetries alone are insufficient to effectively weaponize the semiconductor supply chain. The U.S. case shows how states can overcome their marginal position in one network through cross-network weaponization.

In July 2019, Japan removed South Korea from its list of trusted export countries in what many assumed to be in response to court rulings ordering Japanese companies to compensate Koreans forced to work for them during World War II (Arrington 2019). Countries included on this list are considered to have taken sufficient measures to avoid re-exports of "dual-use products" to black-listed countries and benefit from a fast-tracked import process. Their companies can apply for licenses in bulk, covering multiple products and transactions at once. Meanwhile, companies from excluded countries must apply for an individual license for every transaction involving these sensitive products, which can take up to 90 days to obtain and effectively impede their export (Kim 2021b, 95).

Among all products affected by this decision, three in particular stand out due to their essential role in semiconductor manufacturing and Japan's central role in their production: hydrogen fluoride, fluorinated polyimide, and photoresists. At the time, reports indicated that Japan accounted for as much as 70 percent (hydrogen fluoride) and 90 percent (fluorinated, polyimide, and photoresists) of the production of these components used for semiconductors (Goodman, Kim, and VerWey 2019, 14, 17–8). By limiting the imports of these three products, Japan seemingly threatened to disrupt a third of South Korea's exports and, with it, its entire export-based economy (Ezell 2020). This constituted a chokepoint effect as originally described by Farrell and Newman (2019a, b). The combination of its export control system and the topography of the production network for these three chemicals created an opportunity for Japan to coerce South Korea.

However, Japan's attempt to weaponize these three chokepoints failed. Despite a short-term dominance in these three components production, Japan did not have a dominant position across all three networks and South Korea was able to find alternative supply sources. For example, figure 9 depicts the hydrogen fluoride trade network in 2018, a year before the trade dispute started. Each node represents countries, and each links the value of exports between two countries. The thickness of each link reflects the value of exports and arrowheads point to the importing country. For simplicity, we again only kept trade relations accounting for more than 0.5 percent of the global trade in hydrogen fluoride.

As previously pointed out (see figure 6), China is the main exporter of hydrogen fluoride. Japan only leads in the production of highly purified hydrogen fluoride used in semi-

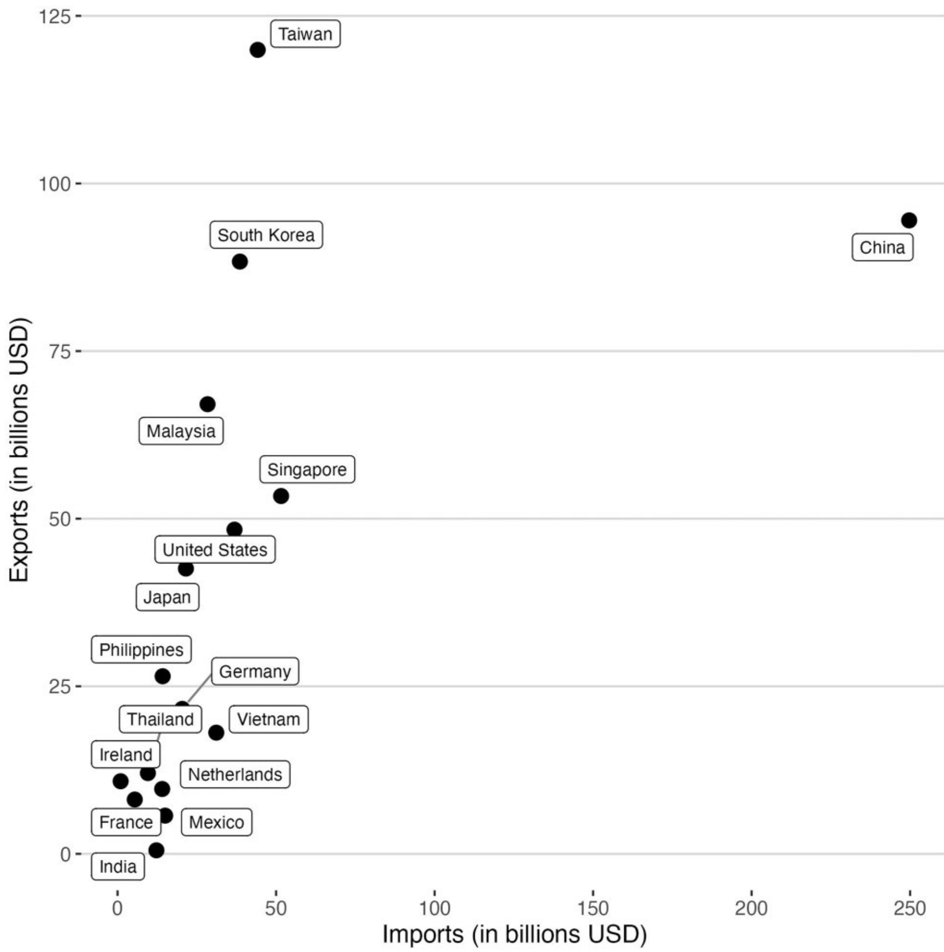

Figure 8. Sum of bilateral trade in assembled semiconductors (HS 8541 and 8542) in 2019

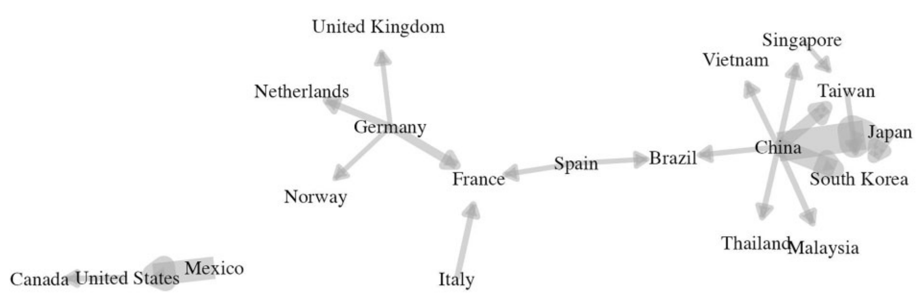

Figure 9. Trade network of hydrogen fluoride in 2018

conductor production (Goodman, Kim, and VerWey 2019,, 14). As figure 9 shows, a year before the trade dispute, Japan imported the unpurified chemical from China before purifying and re-exporting it to South Korea. At the time, most Chinese exports of hydrogen fluoride to South Korea were not used for semiconductor production. Taiwan also had a domestic capacity to purify hydrogen fluoride and exported some to South Korea, but it was marginal in comparison to Japanese exports. As Japan introduced its export restrictions, South Korea had opportunities to replace Japanese imports, chiefly from China. With the support of Japanese firms, it effectively (re)established local purification capacity to meet its needs (Kim 2021a, 2021b). While challenging in the short term and requiring it to temporally tap into its reserves, this process of import substitution appears to have been successful. As figure 10 shows, its imports of Chinese hydrogen fluoride, in effect, grew as Japanese ones came close to nothing. Meanwhile, the value of South Korea's exports of semiconductors in 2021 was almost identical to the peak achieved in 2018, before the trade dispute with Japan.[8] Despite a temporary slowdown in 2019 and 2020 compounded by the U.S. sanctions against Huawei discussed below and the COVID crisis, South Korea remains the second largest exporter of semiconductors behind Taiwan.

While lacking the data to observe the global trade network structure for fluorinated, polyimides, and photore-

[8]According to trade statistics from South Korea's customs service, exports of assembled semiconductors (HS 8541 and HS 8542) were down 1.2 percent in 2021 compared to 2018 (authors' calculus based on the UN Comtrade database).

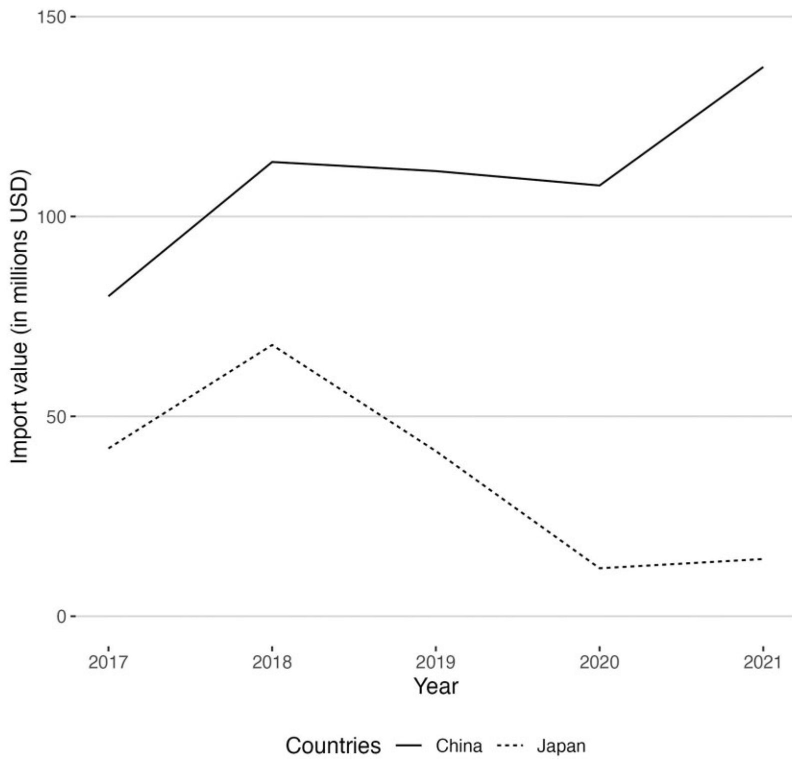

Figure 10. Evolution of the yearly value of South Korea's imports of hydrogen fluoride from China and Japan

sists,[10] South Korea's semiconductor exports indicate that it was also able to access them from non-Japanese sources. Kim (2021a, b) argues that South Korea overcame Japanese restrictions through import substitutions from countries such as Belgium, in the case of photoresists, and increased domestic production. In other cases, Japanese firms moved production to South Korea or third-party countries to circumvent Japan's restrictions. This illustrates that while significant, Japan's position was not as central as it was originally assumed, and that it was Japanese firms rather than Japan itself that were central. Once given sufficient incentive to invest resources, South Korea, Japanese firms, and third-party firms were able to establish rival nodes and connections, reducing Japan's centrality.

By contrast, the U.S.'s weaponization of semiconductors against Huawei has been more successful. However, this was not initially the case. In listing Huawei on the Entity list in 2019, the U.S. hoped to disrupt Huawei's supply of semiconductors in two ways: by prohibiting it from buying American-made semiconductors (which are several generations ahead of what China can produce itself); and by cutting Huawei's subsidiary semiconductor company, HiSilicon, off from crucial software and manufacturing equipment used in production. However, Huawei was still able to buy semiconductors from foundries in Taiwan and South Korea (Bown 2020).

As figure 11 illustrates, the U.S. centrality in assembled semiconductors was too low for it to effectively weaponize the network. Again, each link in the figure connects countries exporting more than 0.5 percent of semiconductors global trade. The thickness reflects the value of exports and arrowheads point to the importing country. In this network, Taiwan and South Korea are the two most central exporters.[11] Moreover, foundries in both countries could not only continue to trade with Huawei but do so on behalf of the American fabless companies that had outsourced their production to them. The Semiconductor Industry Association ended up making the case to the Trump administration that these export control measures only risked leaving American manufacturers of semiconductors worse off than before (Bown 2020). They faced restrictions that companies in other countries did not in selling to the biggest importer of semiconductors (see figure 11), further discouraging investment in their building up their production capacity.

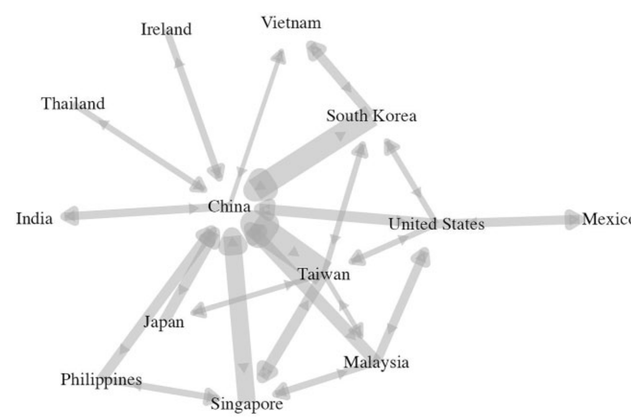

Figure 11. Trade network of assembled semiconductors (HS 8541 and 8542) in 2019

[10]Both products do not have individual HS codes for trade statistics.

[11]China also appears central but mostly because of its imports as the direction of arrowheads emphasizes.

To overcome its marginal position in the production network, the U.S. used the Foreign Direct Product Rule (FDPR) to extend its sanction to third-party suppliers.[12] In an updated version of the rule specifically targeting Huawei, the U.S. restricted the export of foreign-produced semiconductors made using American software or technology. As a result of this change, companies in Taiwan and South Korea faced being cut off from U.S. software, core intellectual property and manufacturing equipment if they continued to supply Huawei (Bown 2020; Capri 2021). It was this measure, taken in August 2020, that significantly disrupted Huawei's supplies of semiconductors. According to Huawei's chairman, the measure costs as much as US$30 billion every year (Pan 2021). Industry reports also indicate that Huawei went from ranking second in global smartphone sales, trailing only Samsung, to falling out of the top five companies (*Canalys* 2021).

In a clear case of cross-network weaponization, the U.S. used its centrality in the design network to isolate Huawei not only from the U.S. but from other major nodes in figure 11 too. As highlighted in the previous section, the U.S. is the most central actor in the design of semiconductors. In effect, every country relies on U.S. technology and software to produce semiconductors. By threatening to cut them off from its chokepoint, the U.S. could thereby force the main producers of highly advanced semiconductors from Taiwan and South Korea to stop exporting semiconductors to Huawei. That is, the U.S.'s centrality in assembled chips (like Japan's centrality in hydrogen fluoride, fluorinated polyimide, and photoresists) was too low to create a chokepoint effect against Huawei. However, unlike Japan, the U.S. was able to use cross-network weaponization to leverage its centrality in the design network to create chokepoints in the networks for assembled chips and production equipment.

The U.S. again used the FDPR and its centrality in the design network to cut off Russia's supply of semiconductors as part of a broader package of sanctions following Russia's invasion of Ukraine in February 2022. It has also more recently sought to restrict all Chinese companies from accessing the most advanced semiconductors, working with its allies in Europe and Asia. In the last section, we discuss what this means for states' power resources.

Design as Structural Power

The U.S.'s success in weaponizing semiconductors against Huawei and Russia demonstrates how important a multi-network analysis is for WI research, and more broadly, how potent cross-network weaponization is for a state's coercive power. Much like how the U.S.'s dominance of finance enables it to impose crippling secondary sanctions, its control over design within the semiconductor industry enabled it to weaponize networks where it lacked sufficient centrality on its own. Below, we argue that the weaponization of the design network reflects the U.S.'s structural power (Strange 1987) within the semiconductor industry.

Structural power is the ability to shape the capacities and preferences of other international actors (Barnett and Duvall 2005, 53). Recently, a literature has emerged that uses the concept of infrastructural power to describe the influence of actors with control over key conduits in the global economy. Notably, infrastructural power has been used to explain how financial actors gain leverage over central banks, which are increasingly relying on global financial markets to execute monetary policies (Braun 2020). While closely linked to the concept of structural power, infrastructural power differs in that it operates *through* existing market structures (Petry 2021, 584). Following our network approach, we understand structural power as the ability to affect the network structure itself, which in the process affects the capacities and preferences of actors operating within them.

Through the weaponization of its firms that design semiconductors, we argue the U.S. exerts structural power throughout the industry. More than determining which international firms can access U.S. technologies, they change the structure of the supply chain itself. In doing so, the U.S. demonstrates dominance over two of the four aspects of structural power identified by Susan Strange (1987): information and production.

First, the U.S.'s position in design allows it to control the distribution of knowledge and information in the industry. Over the years, the U.S.'s dominant position in this information network helped it shape the global semiconductor supply chain through strategic technology transfers with its military allies. During the Cold War, the U.S. attempted to prevent the Soviet Union from acquiring semiconductors and other dual-use technologies through the Coordinating Committee for Multilateral Export Controls (COCOM). Through COCOM, the U.S. and its allies controlled the trade of certain goods to prevent technology transfer from the West to the East via a chokepoint effect (Mastanduno 2021).

Since the end of the Cold War, the U.S. continued to limit the transfer of dual-use technology through the much less restrictive Wassenaar Arrangement, which replaced COCOM in 1996 (Klaus 2003). All these control measures help ensure that critical technology remains under the control of the U.S. and its allies. Meanwhile, network effects create path dependency that reinforces this outcome, as "deep technical know-how and scale" (Varas et al 2021, 4) creates a "success-breeds-success process further solidifying the ability of lead companies to dominate the market" (Grimes and Du 2022, 3). Some have argued that it's "too late" for would-be competitors such as China to challenge the U.S.'s information structural power since the "fundamentals of semiconductor manufacturing are already shaped and innovation patterns are established" (Rho et al 2015, 165) making it near-impossible for latecomers to catch up.

Second, the dominance of U.S. companies in design also translates into productive structural power where they control "who shall produce what, how and with what reward" (Strange 1987, 566). This is notably at the heart of the fabless-foundry production model. For example, the Taiwan Semiconductor Manufacturing Company is crucial in the global supply of semiconductors—including the most advanced ones on the market. However, it is also a foundry specializing in production with, in the words of its founder and former chairman and CEO Morris Chang, no capabilities in design.[13] The U.S., meanwhile, is peerless in design, which is why it was able to use its dominance in it for cross-network weaponization against Huawei. Almost all HiSilicon-designed semiconductors were made by the Taiwan Semiconductor Manufacturing Company, which was not captured under 2019 sanctions on Huawei.

[12]The FDPR allows the Department of Commerce's Bureau of Industry and Security (BIS) to regulate the trade of products produced outside of the U.S. if they use certain American technology, software or equipment in their production.

[13]In an interview with Brookings, Morris Chang stated that "the U.S. has a very good position in semiconductor technology-design, the U.S. has got most of the design capability in the world, the best design capability in the world. Taran has only a little, TSMC has none." For the complete interview, see https://www.youtube.com/watch?v=NwCWYcag5RE

However, because this production depended on software[14] and technology from American companies, it *was* captured under the 2020 FDPR rules (Segal 2021). In other words, dominance in design enabled the U.S. to decide "who shall produce what, how and with what reward" (Strange 1987, 566). While the U.S.'s ability to weaponize design and cut HiSilicon off from critical information and knowledge demonstrates the U.S.'s informational structural power, its ability to use design to cut HiSilicon off from manufactured chips from Taiwan and elsewhere demonstrates the U.S.'s productive structural power.

The alternative for China is to, as South Korea was able to do with purified hydrogen fluoride, develop local capacity. Indeed, China *has* aggressively invested resources in developing an indigenous semiconductor industry in recent years (Weiss 2021). These efforts have enjoyed some limited success, particularly in securing the transfer of know-how, hardware, and industry connections from Taiwan (Klaus 2003; Chu 2014). However, while companies have been willing to move labor-intensive semiconductors production into China, they have strategically withheld more advanced manufacturing processes. The knowledge-intensive stages of production are also subject to more stringent state controls (Rho et al 2015; Grimes and Du 2022).

That is, it may appear as though China's investment in the industry has translated into significant influence over production, and therefore productive structural power. After all, it has the largest share of the market for assembled chips (Varas et al 2021—see also figure 8). However, in reality, China's influence remains limited. Indeed, despite accounting for over a third of world semiconductor exports, it captures just 9 percent of the industry's added value versus 38 percent for the U.S. (Varas et al. 2021). Moreover, China's growing production capacity may benefit American companies that capture most of the added value from the production of semiconductors, which they can then re-invest in R&D activities, further entrenching the U.S.'s dominant position in the design of semiconductors. In fact, the Pentagon raised concerns in 2020 that stricter sanctions on Huawei could limit innovation in the U.S. by reducing the revenue of American technology companies (Segal 2021).

There are important policy implications of this analysis. Recently states have taken a great interest in the strategic importance of improving self-sufficiency in semiconductor production. While pandemic-related supply chain issues have contributed to concerns over self-sufficiency, security concerns are also forefront of these initiatives. In addition to China's efforts, the European Union is also pursuing a €42 billion initiative to double its global market share to 20 percent by 2030. Meanwhile, the U.S. has enacted legislation, the so-called CHIPS-Act, that allocates $52 billion in subsidies to "strengthen American manufacturing, supply chains, and national security" (The White House 2022). Specifically, the CHIPS Act is aimed at addressing the U.S. decline in semiconductor manufacturing. For example, when signing the Act, the Biden Administration stated that "America invented the semiconductor, but today produces about 10 percent of the world's supply—and none of the most advanced chips. Instead, we rely on East Asia for 75 percent of global production" (The White House 2022). From China to Europe to the U.S., the global economic superpowers are locked in a battle to win a greater share of the industry.

However, our analysis demonstrates that focusing on a state's share of semiconductor production can obscure the distribution of power in the market. Namely, this narrow view underplays the U.S.'s structural power in the industry while also overstating the influence of China. That is not to say that production is irrelevant to the distribution of power in the semiconductor or other advanced manufacturing industries—production is clearly important to productive structural power. Moreover, information structural power may support productive structural power, however, the reverse is also true. Research has demonstrated how the erosion of the U.S.'s manufacturing base is weakening its technological leadership, for example, (Weiss and Thurbon 2018; Weiss 2021). However, our contribution to cross-network weaponization demonstrates that centralization in some networks—in our case semiconductor design—can be more useful for WI than centralization in other networks.

However, there are clearly limits to this. While China may lack the same capacity to use WI in the semiconductor industry as the U.S., its dominance in the market for assembled semiconductors and other aspects of the supply chain nevertheless affords it some security. The U.S. has been successful in leveraging its dominance in design to frustrate and stymie the Chinese semiconductor industry through chokepoint effects, however, China remains too deeply embedded in global supply chains to be fully excised. This demonstrates not only the limits of U.S. structural power in this respect but also WI itself. Through WI and cooperation with its allies, the U.S. is effectively trying to create an arrangement similar to COCOM, whereby critical and dual-use technology is allowed to be internationalized but only among a select few allied states. However, the use of structural power to "reshore" industry and bend global supply chains into more politically appeasing configurations is a far more difficult task than can be achieved through chokepoint effects alone.

Conclusion

This article applied network analysis to examine how WI has been successfully used in the semiconductor industry. However, rather than examining the industry as a single network, focusing only on the market for assembled semiconductors, we take a multi-network approach. Specifically, we disaggregate semiconductor production into four distinct yet inter-connected networks: (1) design, (2) materials, (3) production equipment, and (4) assembled chips. Our analysis shows that each network has a different topography, with no countries enjoying centrality across all four. Specifically, while the U.S. enjoys high levels of centrality in design, it has a limited to marginal presence in the other networks. China, meanwhile, has next to no presence in design but holds a more central position in the network for assembled chips and, most of all, for their final assembly in consumer electronics.

Our multi-network approach more accurately reflects the complexities of globalized supply chains. It also demonstrates how states can use chokepoints in one network where they do not have a central position, through the control of a chokepoint in another network where they do—what we call cross-network weaponization. The article then analyzes how the U.S. sanction against Huawei is an example of cross-network weaponization. The U.S.'s small share of the market for assembled chips meant that when Huawei was put on the

[14]Significantly, electronic design automation (EDA) software was up to now excluded from U.S. sanctions following years of lobbying by the American semiconductor industry (Khan 2020, footnote 23). Recent reports indicate that the U.S. could, however, be ready to include these essential tools in today's semiconductor production (Yang 2022).

entity list in 2019, it was able to find alternatives to U.S. semiconductors (which are too advanced to be manufactured in China) through third-party markets such as Taiwan and South Korea. However, the U.S. later used FDPR rules and its unrivaled centrality in design to threaten secondary sanctions against these third-party suppliers, effectively cutting off Huawei's access to the most advanced semiconductors. That is, the U.S.'s WI had its origins in the design network but was realized as a chokepoint in the network for assembled chips. The U.S.'s sanctions against Russia similarly used cross-network weaponization in this way.

Last, we argue that the capacity for cross-network weaponization is a manifestation of structural power. First, the U.S. has informational structural power as its dominance in design enables it to determine who has access to critical technical information and knowledge. This dominance has been a mainstay of the semiconductor industry since the Cold War, when access to dual-use technology, including semiconductors, was restricted to the U.S.'s political and military allies through COCOM. Second, through the fabless-foundry production model, whereby some firms specialize in the design and outsource production to manufacturers, the U.S.'s dominance over information translates into productive structural power as well. By determining who has access to critical technology, the U.S. can also determine "who shall produce what, how and with what reward" (Strange 1987, 566).

This analysis demonstrates that preoccupation amongst policymakers with the share of the trade in assembled chips can obscure the U.S.'s influence in the industry while also overstating that of China. The precise mechanism that creates this structural power, however, is not addressed here and would be an important area for future research.

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Conflict of interest

The authors declare no conflict of interest.

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