Wilson Center
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Kissinger Institute

2023–24 WILSON CHINA FELLOWSHIP

Rethinking Export Controls: Emerging Technologies, Industrial Organization, and US-China Relations

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Abstract

For decades, US-China relations were characterized by deep interdependence producing mutual benefits through global value chains (GVCs). Today, geopolitical tensions over advanced technologies are undermining engagement and unwinding GVCs. At least since 2018, American policymakers have returned to a Cold War era-like strategy of leveraging export controls to degrade Chinese military capabilities by restricting Chinese access to American technologies. The central assumption is that American technological dominance in select specialized areas creates 'chokepoints' (measured by market share) that can be 'weaponized' towards American strategic ends. By contrast, critics doubt the effectiveness of export controls in achieving these goals based on two basic arguments: either Chinese firms will figure out 'workarounds' or China will 'innovate' their way through the controls. This paper argues that changes in global industrial organization (GVCs and ecosystems) raises issues for both supporters and critics of American export controls. On the one hand, new industrial organization raises questions about some core principles, measurements, and assessments of export controls. Wittingly or not, critics generally accept these same principles, measurements, and assessments, but come to a different conclusion. However, through the lens of organizational governance, this paper finds that American export controls are at risk of relying on 'mirage' chokepoints, inducing unintended consequences, and generating new trajectories of Chinese innovation, which could lead American policy interventions to become overly expansionary and less effective. America's export control regime needs to adapt to the new industrial organization of GVCs and ecosystems.

Policy Implications and Key Takeaways

- Industrial organization has undergone radical changes, and export control policies need to adapt accordingly.

- Traditional methodologies, such as assessing American chokepoint strength through 'foreign availability' and determining American coercive power through US market shares, are less effective today and could lead policymakers to become overconfident in America's coercive potential. For instance, American chokepoint strength appears high in semiconductor inputs (like EDA software and equipment) but these are effective only if the chokepoints are part of a linear supply chain, and the final product is a necessary input to achieve China's strategic ends. Since these assumptions do not always hold, policymakers should analyze the broader business organization when evaluating American coercive potential.

- Similarly, assessments of the impact of export controls on American industry and innovation (such as 'loss of sales') are also problematized by more complex forms of business organization. For instance, American firms acquire many resources beyond revenue derived from direct sales relationships. There are second-order effects of export controls, such as American firms' access to the network of suppliers, users and complementors of the firms targeted by export controls. Policymakers should also consider the broader industry ecosystem when evaluating impacts on American industry.

- Export control policies that focus on controlled product lists are less effective when applied to advanced technologies, in which complex cooperative relationships among an ecosystem of firms are central to innovation, not just the market accessibility of advanced American products. For instance, firms sometimes cooperate extensively even when they lack a buyer-supplier sales relationship, such as semiconductor foundry cooperation with EDA software firms. Export control policy should focus more on the diversity of inter-firm network ties and the structure of industries for targeted firms, rather than simply the impacts of cutting off access to American products.

- This complexity in industrial organization requires integrating unbiased expertise in business organization into policymaking, which is different from (but complementary to) the already extensive technical knowledge of emerging technologies that exists within government. Similar to technical expertise, industrial organization is also industry-specific and varies widely. Export control strategies should incorporate insights on industry-specific business organization.

- Given complex firm networks and the diversity of inter-firm linkages, export control policymakers should consider a broader range of unintended consequences for American and allied country firms, as well as targeted firms and countries. For instance, Chinese company and government counter-strategies to US export controls will be more diverse than the reactions most commonly discussed in the policy community, such as Chinese 'workarounds' (like IP theft and shell companies) or China's strengthened determination to 'catchup' through innovations. Given the flexibility of industry ecosystems, counter-strategies could avoid export controls through many additional pathways: complete product redesigns, innovative alternative pathways to the same strategic ends, and the rerouting of innovation into new directions. Policymakers should expect and prepare for a wider range of counter-strategies in the medium term.

Introduction

Over the past years, the US-China relationship has deteriorated with a speed few could imagine possible. For decades, China was a central stakeholder in a global economy deeply interdependent through global value chains (GVCs).[1] However, geopolitical fears have called this interdependency into question. Never before have countries, firms, people, and knowledge been so interdependent, while simultaneously perceiving each other as national security threats. And paradoxically, the very elements that allowed interdependence to flourish (complex GVCs) are precisely the causes of today's national security concerns.

The geopolitics of technology are arguably the most concerning and consequential in the long run. In 2022, US Secretary of State Blinken highlighted technology as the root of the security problem, calling it "an inflection point" in which "the post-Cold War world has come to an end, and there is an intense competition underway to shape what comes next. And at the heart of that competition is technology."[2] Export controls have become the primary American policy tool in our technological rivalry with China. These began with the Obama administration, rapidly escalated through the Trump administration's export controls, and exponentially expanded through the Biden administration's China-wide export controls on emerging technologies. While many may want to wish away the national security concerns and return to a purer era of engagement, the conflict is institutionalized in both the United States and China.[3]

The key argument of this paper is that fundamental changes in international industrial organization—GVCs and ecosystems—are not being matched with changes in export control principles, measurements, and assessments. Cold War-era policy approaches are based on 20th century industrial organization and rest upon principles such as the strength of American technology chokepoints ('foreign availability') and measurements like American firms' market share, among others. However, over the past decades, production has fragmented (outsourced) and internationalized (offshored), creating increasingly complex GVCs, which generate new forms of cross-border, inter-firm governance. Furthermore, the speed and complexity of advanced technologies have forced firms to organize into complex and open innovation ecosystems linked together in diverse ways, which blur firm and product boundaries as even competitors regularly cooperate and collaborate, sometimes called 'coopetition' among 'frenemies.'

As such, American export control policies risk mismeasurements and misinterpretations of this new industrial organization, which can lead to overconfidence in American coercive power. Export controls may be founded upon 'mirage' chokepoints, induce unintended consequences, stimulate Chinese innovation beyond chokepoints, and trigger an expansive utilization of controls, with reduced chance of achieving policy goals and potentially undermining American and allied innovation.

The new industrial organization suggests changes in export control policies. Today, access to corporate partnerships is more important for long-term sustained innovation than access to high-technology products. For policymakers, this means that instead of controlling lists of dual-use technology products, policymakers should consider the type and the structure and diversity of inter-firm ties by which advanced technologies come to market.

This is particularly important today because commercial firms (not military-oriented ones) are determining the direction of the technological leading-edge of most dual-use products. This also implies that policymakers must carefully consider a broader spectrum of factors when defining policy 'effectiveness' on targeted firms and countries, and when considering the second and third-order effects on American and allied firms. Government agencies require additional types of unbiased expertise in business organization, which complements but is distinct from purely technical knowledge of the advanced dual-use products.

The US-China Security Dilemma and Contemporary Export Controls

Deep interdependence is not inherently a security threat. However, the US-China security dilemma is so acrimonious for three fundamental reasons: first, emerging technologies blur military-commercial 'dual use' like never before; second, both countries are dependent on their commercial firms to advance their military leading-edge; and third, firms in advanced technologies must cooperate with each other or perish, creating increasingly interdependent GVCs and ecosystems. That was not always true. During the Cold War, dual use technologies, like nuclear, had clearer thresholds to differentiate military and civilian usages, such as the level of uranium enrichment. Second, they were easier to control because they were more likely produced by a small number of vertically integrated firms or defense prime contractors. Today's emerging and foundational technologies that are increasingly falling under US control (like AI, semiconductors, high-performance computing or HPC, among others) are primarily commercial technologies that are developed, produced, and used overwhelmingly by commercial firms, even though they have military usages.

Finally, and most centrally for this paper, industrial organization has fundamentally transformed. During the Cold War, innovation and production were largely nationally based and products were more commonly produced in-house by large, vertically integrated firms. As discussed in detail below, over the past decades and particularly in the most technologically advanced sectors, firms have intensely specialized, and firm boundaries have opened and blurred, creating complex ecosystems of suppliers and complementors that jointly collaborate and innovate in diverse ways. To survive, firms openly innovate through joint R&D, innovation platforms, common standards, and open-source software, among other methods.

How can the United States balance these conflicting tensions between military-civilian technologies, and globally fragmented production and open innovation? The current US answer sounds correct. National Security Advisor Jake Sullivan pithily describes America's strategy as protecting "a small yard with a high fence,"[4] meaning that America will control China's access to key American commercial technology in narrow but critical areas to minimize damage to American firms, competitiveness, and allies and partners. However, this assumes military-commercial lines are clear, innovation is geographically and organizationally bounded, and GVCs are easily partitioned along national borders.

But industrial organization is not so simple, and, consequently, American rhetoric dramatically diverges from its ever-expanding export control policies. For instance, since 1997, out of more than 800 Chinese organizations placed on the Entity and Unverified Lists (the key export control list), over 80 percent of them were designated since 2018 alone.[5] When Secretary Blinken's declared the 'inflection point' in October 2022, the Commerce Department instituted unprecedented China-wide controls on critical digital technologies, including AI technologies. These were expanded in October 2023, and more are potentially in the pipeline.

The fragmentation of global production is creating a murky middle in technologies, thereby changing policy. There has been a blurring of military and commercial technologies, and an increasing reliance of military technologies on commercial firms and commercial innovations. And the acceleration in commercial innovations is an outgrowth of the fragmentation, specialization, and globalization of innovation, which makes the locus of innovation unclear. These transformations undercut the goal of minimizing export controls and can undermine their effectiveness. As discussed next, although the underlying industries have transformed, export control policy principles, measurements and assessments have not changed, which this paper describes as 'classic' export controls.

'Classic' Export Controls: Policy Principles, Measurements, and Assessments

Despite this new industrial organization and changes in technology, the key principles, measurements and assessments of classic export controls have not altered. This paper focuses on several core principles of classic export controls, which are being challenged by new industrial organizational forms and which may require reevaluation. For instance, one of the central pillars of effective export controls is the degree of foreign (non-US) availability of the concerned technology. 'Foreign availability' has been a long held principle of export controls, because they will be ineffective for technologies that are more widely available or easily substitutable.[6] Today, the mantra of 'weaponizing' technological 'chokepoints' proliferates in discussions of export controls among think tanks, academics, and practitioners, which is often measured as a simple calculation of the American share of global markets of particular 'essential' product categories.[7] The effectiveness of chokepoints is intended to measure American coercive power through export controls (and sanctions), and these ideas have come to dominate the discourse on targeting cutting-edge commercial technologies, like semiconductors, semiconductor manufacturing equipment (SME), AI technologies, and high-performance computing. At its heart, chokepoint strength and market share metrics are judgments about the underlying organization of industry and products, which we return to later.

The principle of chokepoint strength (determined by alternative foreign availability) interacts with several other important policy principles, such as those concerning 'black knight' countries, the risks of creating an uneven innovation playing field, legal extraterritoriality, and multilateralism. First, drawing from the sanctions literature, the relative strength of a technological chokepoint influences the chances of a 'black knight' country coming to the aid of a sanctioned country or firm.[8] This was quite common during the Cold War,[9] but it is also a hot button issue today, especially regarding Chinese provisioning of Russia after the invasion of Ukraine.

Second, it is feared that US controls create an uneven playing field that unfairly hampers American firms, thereby undermining American innovation. If only US firms are restricted from exporting to major clients (like those in China), but European, Japanese, or other high-tech suppliers are free to capture the market shares abandoned by American firms, then US companies both lose revenue and suffer reputational costs as 'unreliable suppliers,' which some authors characterize as "a discriminatory, sector-specific, and therefore unfair tax [on American firms] to finance foreign policy."[10]

Chokepoint strength also impinges upon the application of US extraterritorial controls (called 'foreign direct product rules,' or FDPR), which are highly complex and controversial, but potentially resolve the problems of black knights and uneven playing fields, while also improving effectiveness. For decades, the Commerce Department's Export Administration Regulations (EAR) have regulated foreign-made items if they contain more than a *de minimis* amount of controlled content or are Wassenaar-controlled "national security" items produced directly from US-origin technology that is also controlled for the same reason.

Broadly speaking, this means that technologies which are produced with or contain within them US-origin technologies over a certain threshold amount are also controlled items, even if they are produced by wholly foreign-owned entities and outside American territorial jurisdiction, including by companies of our allies. These extraterritorial controls are highly controversial and extremely complex, both because of the expansion and complexity of EAR regulations, but also because the fragmentation of production through GVCs has opened up innumerable avenues for US-origin technologies to be designed into products.

Finally, and most importantly, chokepoint strength impinges upon another central pillar of export controls: unilateral controls (and extraterritoriality) should be limited, and US policy should favor multilateralism. For instance, in Senate testimony, Obama-era Assistant Secretary of Commerce Kevin Wolf stated "it is rare that the US will have, or could keep long, a monopoly over a commercial technology," concluding that "the obvious answer… is for our allies to impose the same controls and licensing policies."[11] Some argue that when Commerce placed export controls on commercial-oriented technologies in the post-Cold War period (such as commercial satellite to China), they proved "at best a tool of delay, [because] Chinese progress has not been halted [due to] the emergence of alternative sources for talent and technology, espionage, and ebbing US competitiveness.[12] In 2018, multilateralism was explicitly enshrined in new export control legislation (ECRA),[13] has been expressed publicly through official channels to European allies,[14] and is widely accepted in academia and think tanks.[15]

These various principles and policy tools are interactive and rest upon the foundation of chokepoint strength, usually measured as American market share, and the speed of technological diffusion. For instance, higher chokepoint strength encourages American unilateralism and extraterritoriality, which (if successful) may preserve a level playing field to maintain American firms' competitiveness and innovation. By contrast, lower chokepoint strength reduces the shelf-life and effectiveness of unilateral American controls, and thereby makes a multilateral approach more attractive, which simultaneously reduces American temptations to utilize its extraterritorial powers. In a word, a lot rests upon assumptions concerning techno-organizational factors, like industry structure and concentration (existence of chokepoints), industrial barriers to entry, and pathways of technological diffusion. If industrial organization transforms, this may have important consequences on policy.

Challenges to Classic Export Controls: Emerging Technologies, GVCs, and Ecosystems

The principle of chokepoint strength, its measurement as market share, and the many important affiliated principles related to it, certainly hold true in many industries and products, particularly ones rooted in 20th century industrialization. But, usage of the framework often belies several implicit assumptions about industry organization and technology, and by extension the nature of policy controls. This paper examines differences in products and firm relationships along several dimensions, including product delivery, alienation (of property rights), maintenance, extent of explicit coordination between firms, and sunk costs.

Generally speaking, export controls are imposed on fairly conventional transactions, namely that there are two actors in the transaction—buyer and seller—and that product ownership is transferred by the American seller to the targeted foreign buyer. Thus, firms (and their products) are discrete entities (firm boundaries are relatively closed) and alienation occurs at a discrete time. The product or service is wholly owned by the American supplier and then 'alienable' (rights are transferred) to another firm or organization. Sunk costs become important at the point of alienation of the product or service. While ownership, delivery, and alienation are discrete and clean-cut, after-sale product maintenance may be more complex in terms of use of third parties, as well as determining liability and payment. Overall, buyer-seller interactions are assumed to be relatively arms-length.

This is how most people commonly think of transactions, and if they hold true (which they often do), then in certain situations, chokepoint strength (high market share) may be a fairly straightforward way of thinking about American economic coercive potential. However, not all industries or products abide by these principles. By focusing on chokepoints and market shares, it creates the impression that all industries can be analyzed in similar ways, and that the concept of market share (high/low) has the same meaning across industries. These are reasonable assumptions in many industries and for many products. But, they are less applicable in more advanced technologies, like ICTs, which are the industries that the United States has imposed the most controls on China.

These assumptions hold less true today because since the mid-1990s, firm boundaries have become blurred as they increasingly engage in 'open innovation,'[16] ecosystems of firms jointly create value,[17] and many transfers do not include the formal alienation of goods, but the informal (non-proprietary) flows of valuable information and knowledge. Thus, the product that appears on controlled lists is less important compared to the firm linkages that stitch together innovation and product ecosystems and their structure.

In the most innovative, cutting-edge industries, several factors interact to drive firms to collaborate (even with direct competitors), open and blur their firm boundaries, and jointly produce products within ecosystems. These factors include: when technology is extremely complex, when there is greater uncertainty in best practices and innovation pathways, when knowledge is more tacit (non-codifiable), when expertise is highly specialized and widely dispersed, and when the speed of innovation is extremely rapid.[18] Thus, in order to remain competitive, firms need to tap many sources of information and openly collaborate across many knowledge domains to maintain rapid product development and achieve novel recombinatory technical outcomes.[19]

Under these conditions, firms are more successful when they openly collaborate, establish more partnerships with other firms, and thereby reside at the 'core' of innovation ecosystems.[20] Thus, since at least the mid-1990s, industrial organization has shifted in a manner rendering a firm's network of linkages more important than the products. At the same time, a substantial amount of knowledge and value exists within the ecosystem and not embedded in discrete firms or their products. Thus, controlling access to networks should be more central to export control policies than controlling products. This means that inter-firm linkages and locations in ecosystems should also be the focus of controls, not only products, end-users and end-uses.

While the above addresses the innovative processes that produce products, even some high-tech products themselves are 'open,' never fully alienated, and created collaboratively. Oftentimes, they are not discrete products, or 'wholly owned' by a single, well-defined firm who transfers ownership at a discrete moment. For instance, this is the case with open-source software, where developers license their code for 'free'—both monetarily free but also free for anyone to use and alter the code. Very significant portions of our digital world are built upon this open, collaborative, and free intellectual property. In open-source, knowledge and value are disembodied from the products, residing as club goods or public good resources in the network of linkages. Furthermore, the transfer of value in open-source depends simultaneously on multiple firms who share club good or public good resources, in which products are continuously altered.

Some of these characteristics are also true of digital platforms. We use consumer-facing platforms every day, such as the Apple app store, Uber, or Amazon. Platforms are distinctive because value derives from the innumerable 'complementors' who engage and contribute to the platform and the equally innumerable 'users' of those services. Like any marketplace, Uber is valueless without the drivers and riders; Amazon is valueless without storefronts and consumers; and app stores are valueless without developers and users.

This is achieved because the platform leaders partially open up their intellectual property to encourage the building of the ecosystem. Thus, platform products are not self-contained products of the putative lead firm. Rather, the products and services are jointly created through a large ecosystem of firms and users (sometimes many millions), often dispersed across the world. Value is enhanced by the sheer size of the ecosystem, meaning each actor contributes to the value of all the other actors, even if they never transact.

This open innovation, blurring of firm and product boundaries and knowledge flows can impact all of our dimensions, including innovation, modes of product delivery, alienation, and maintenance. Across these domains in advanced technologies, it is sometimes hard to define them as the result of discrete firms alienating discrete products. Rather, innovation and products derive from large groups of openly collaborating firms using club good or public good resources, in some cases not explicitly owned (such as open-source software) , in which products are constantly altered.

This openness and lack of firm and product boundaries raises questions about list-based controls. It means that network linkages are the core of these products, and it is access to linkages and disembodied knowledge (not just discrete firms, their products, and their embodied knowledge) which are valuable assets for Chinese firms. When these conditions are met, it suggests that export controls should expand from list-based technology tools to controls over inter-firm linkages within broader innovation ecosystems.

How do inter-firm linkages and ecosystems impinge on export controls? I begin with very brief reviews of key literatures (one on GVC linkages, one on ecosystems) that provide a foundational vocabulary and framework, and then I turn to some empirical examples to illustrate their utility.

Inter-firm Linkages in GVCs

Global value chains (GVCs) have proliferated since the 1990s as production has increasingly fragmented and internationalized. GVCs are complex networks of trade, investment, and knowledge flows, within which firms intensely specialize on their core competencies and outsource non-core tasks to other equally specialized firms.[21] This results in the *functional integration* of countries,[22] which provides enormous benefits to firms and sometimes countries.[23] This fragmentation of production has spawned new ways by which firms cooperate and interlink, called inter-firm 'governance.'

The mutual, interactive impacts between technology and industrial organization are extraordinarily complex and beyond the scope of this paper, but suffice it to say that causality between them is circular.[24] Nevertheless, firms interlink in diverse ways across innovation, delivery, alienation, and maintenance. The type of firm linkage has important implications for how they react to exogenous shocks like export controls. For instance, in one set of GVC theories, different combinations of three variables lead to five modes of inter-firm governance.[25] The three variables include: the complexity of information exchanged between firms; the codifiability of that information; and firm capabilities.

By combining them in different ways, the three variables yield five governance types: 1) simple *market linkages*, governed by price; 2) *modular linkages*, governed by standards, in which complex information is codified and made available at relative arms-length to competent suppliers, creating distinct innovation 'modules';[26] 3) *relational linkages*, governed by inter-firm trust and reputation where complex and non-codified (or 'tacit') information is exchanged between partners who each invest in co-specialized assets;[27] 4) *captive linkages*, governed by powerful lead firms whose less competent suppliers are controlled by precise protocols;[28] and 5) *hierarchy* or linkages within a single firm, governed by managerial fiat. Beyond these, there are other forms of governance, including the digital platforms, discussed earlier.

Ecosystems: Firms Within a System

GVC linkages are dyadic. While two firms are sometimes defined as an ecosystem,[29] in most cases, firms operate within a broad collective of firms (like platforms with potentially millions of actors), each with distinct roles in the ecosystem. The structures of ecosystems are important because export controls that block some nodes within an ecosystem both may alter the ecosystem, but also stimulate new avenues for innovation as an unintended consequence. At the broadest level, ecosystems are "an interdependent network of self-interested actors jointly creating value,"[30] in which firms are formally independent, but informally interdependent—in other words, "interrelated organizations [with] significant autonomy."[31]

Ecosystems have two key differences with GVCs.[32] First, while ecosystems and GVCs both are collectives of organizations that usually interlink without direct ownership ties, ecosystem firms also can be bound together without formal contractual ties, such as through the knowledge flows discussed earlier. Second, ecosystems are not dyadic, nor are they "decomposable to an aggregation of bilateral interactions."[33] The key feature is that multiple firms mutually and simultaneously impact each other, which are not reducible to a series of dyadic linkages.

Ecosystems come in many varieties. Some authors focus on the degree of complementarity between firms, which has implications for chokepoint strength. Strong complementarity is when two products are indispensable to each other and hence value generation is only possible when combined (such as lock and key). Weak complementarity is when substitutes are available. However, complementarity is not always bidirectionally identical. For instance, when one element is strong (indispensable) and the other is weak (replaceable), this creates an *asymmetric* complementarity.

The digital platforms discussed earlier are examples of asymmetric complementarity because the platform leader (Apple) is indispensable, but the many complementors (mobile apps) and the many users (app consumers) are *individually* replaceable. However, Apple is completely dependent on its complementors and users *as a group*, because the app store platform has no value without its ecosystem of complementors and users. Furthermore, as the ecosystem grows larger, value increases for everyone, which reflects its multilateral nature. While Apple is well-known to consumers, platforms are ubiquitous in ICTs—both consumer-facing and producer-facing.

Ecosystems are double-edged swords for export control senders and their targets alike. As discussed previously, the key goal for senders in this new world of fragmented and open industrial organization should be to sever the most indispensable network ties of targets within ecosystems. However, ecosystems also offer substantial flexibility that allow targeted firms to repurpose their resources to pursue alternative innovation trajectories. As discussed below, this is particularly the case in digital ecosystems where many firm linkages are governed by modular ties, called 'massive modular ecosystems' (MMEs).[34]

Empirical Case Studies

How do these concepts relate to export controls and how are they impactful? This final section provides brief vignettes of export controls on Chinese firms, first in the context of differentiated GVC linkages, and then second within a complex ecosystem. Two types of GVC linkages are compared, using the example of two keystone Chinese technology firms—Huawei (a telecommunications firm) and SMIC (a semiconductor foundry). The basic point of the comparison is that despite common circumstances in terms of chokepoint strength and export controls, the type of linkages (across innovation, delivery, alienation, and maintenance) intervenes by strongly influencing the short-term and arguably the long-term impact of export controls.

Very briefly, export controls caused an immediate crisis for Huawei given the nature of its linkages, but the company could recalibrate for longer-term recovery. By contrast, export controls counterintuitively were a boon to SMIC, but its longer-term prospects are grimmer. Subsequently, the section turns to ecosystems to illustrate both the constraints of some ecosystems (like platforms), and the substantial 'flexibility' that Chinese firms have within a digital ecosystem, compared to the more common framing of chokepoints in a linear GVC.

GVC Linkages

Since 2017 or 2018, American export controls on Chinese firms in ICTs have leveraged American dominance of key digital products, particularly in semiconductors. Some key American chokepoint strengths include electronic design automation (EDA) software used by chip designers (like Huawei's HiSilicon subsidiary) to create digital 'blueprints' of chips. These blueprints are then physically manufactured into tangible chips by foundries (like SMIC), which require critical semiconductor manufacturing equipment (SME) such as American-dominated deposition machines, among many others.

Globally, American firms dominate several of these product categories. Thus, through the lens of chokepoint strength, this is the best possible environment for effective controls and for American unilateralism. For instance, American EDA firms or US-origin technologies dominate over 90 percent of global market share.[35] For deposition machinery (only one category of SME, albeit an essential one), American firms control around 90 percent in several deposition machinery categories, and 60–75 percent market share in others.[36]

Classic export control principles would predict relatively identical outcomes given the consistent and extremely high American market shares, which are indicative of exceptional chokepoint strength and thus a lack of available alternatives or substitutes. However, there are significant differences in inter-firm governance across these products, and so based on governance, one would predict variation in the impact on Chinese targets.[37]

Using the governance framework above, EDA company ties are highly 'modular' when interacting with clients like Huawei, during which explicit coordination is minimized, interactions are fewer, and sunk costs are less. This is because the product is alienated through short-term software licenses, delivered in hybrid methods partly by internet, updated and maintained remotely, and can be supplied (or withdrawn) immediately. There is less direct contact between the software engineering teams of the three dominant US companies and their client teams, because they 'interact' indirectly through the standardized software interfaces, which allow extremely complex information flows to occur at relative arm's length. These are features of modular linkages.

By contrast, SME companies engage through relatively more 'relational' governance with their clients, the foundries, which entails substantial sunk costs and direct cooperation between engineering teams. SME suppliers sell very complex machinery that must be physically installed on location in semiconductor fabs (like SMIC) around the world. It must also be regularly serviced and maintained by engineers (often employees of the supplying company), who sometimes live and work near their client's fabs to conduct training, repairs, and maintenance. Once installed, they cannot be removed. However, after-sales software updates have become ways in which suppliers remain engaged following purchase, along with maintenance and repairs.

As empirical illustrations, this paper compares Huawei and SMIC—two of China's premier ICT companies and both deeply enmeshed in the global semiconductor industry. SMIC's entire business focuses on semiconductors (as a manufacturer or 'fab'). Huawei is primarily a telecommunications company (infrastructure and consumer). However, one of the core advantages that differentiates Huawei is its internally designed chips at the global leading edge.[38] In fact, American export controls drove these two firms to collaborate with each other when Huawei-designed chips no longer could be manufactured by non-Chinese foundries, thus leading Huawei to source manufacturing services from SMIC.

Huawei (through EDA, OS, and manufacturing) and SMIC (through SMEs) were both strongly impacted by US export controls. Huawei was placed on the Entity List (EL) in May 2019. This expanded via extraterritorial controls (foreign direct product rule, FDPR) in May and August 2020, the last of which intended to cut off Huawei from all chips and tools using US-origin technology. SMIC was initially placed on the EL in September 2019, which was also expanded in December 2020. However, despite similar American chokepoint strength, similar timing, and similar types of export controls, the impact proved very different due to the two companies' unique inter-firm ties and nature of their technologies.

Huawei's revenue sharply declined by 29 percent in 2021 from 891 billion RMB to 636 billion (per Huawei annual reports), with most of the impact falling upon its consumer products division (like smartphones). In an immediate fire sale in October 2020, Huawei quickly sold off their low-medium end consumer smartphone brand (Honor) to a consortium of state-backed Chinese investors to both allow the product line to survive, but more importantly to conserve its internal resources (especially chip inventories it had been building since the ZTE controls) for its pillar products.

Given that licensed EDA software can be cut off instantaneously (and to a lesser extent, so can the final manufactured chips from the foundries), it generated a crisis for a company of such scale and with such reliance on its own internally designed chips. By August 2020, the controls were extraterritorial, barring the sale of all finished chips and software tools using US-origin technology, regardless of country of origin. It is ironic that Huawei's exceptional capabilities in internally designing leading-edge chips were a huge advantage during an era of open trade but has been turned into an additional liability.[39]

However, although it experienced an immediate crisis, Huawei's longer-term prospects are stronger due to its capacity for strategic recalibration. For instance, Huawei announced in 2022 a corporate reshuffling which made several product lines independent business segments, including cloud computing, digital power (applying compute to energy industries), and intelligent automotive (autonomous driving, smart cockpit systems, and vehicle connectivity). Compared to its traditional telecom equipment product lines, these are more software-intensive products.[40]

Software is double-edge in terms of export controls. While the *supply* of software products can be cut off immediately (like EDA software), the *production* of software can be done with fewer external partners, given the same lack of dependency that is the hallmark of modularity, in addition to the enormous global public good supply of open-source software. Thus, the modular and open-source nature of software makes its internal production more coercion-proof, compared to hardware which relies on more external partners. Thus, Huawei's relative shift towards more software-oriented products will make it more coercion-proof in the future, based on the mode of inter-firm governance and differences in Huawei's ability to transact.

On the other hand, SMIC was equally impacted by export controls but in counterintuitive ways. Given its substantial sunk costs in SMEs, SMIC had less opportunity to undergo a long-term strategic pivot like Huawei. However, in the short-term, it was better positioned to milk its installed base of equipment without fear of instantaneous interruption. Once SMIC was hit by its second round of export controls, it lost access to high-end SMEs (and American engineers to repair them), which are used for more advanced chip manufacturing.

This set off a frenzy of changes. Using SMIC quarterly financial reports to analyze the 12 quarters (3 years) prior to and after export controls, SMIC clearly was impacted, and attempted to redirect its operations, but in far more limited ways. In contrast to Huawei's initial nosedive, after export controls were imposed, SMIC's revenue doubled from 5.8 billion RMB (2019Q3) to 13 billion RMB (2022Q3), gross profits rose by 327 percent from 1.2 billion to 5 billion RMB, and operating profits rose nearly 10-fold from 330 million to almost 3.27 billion RMB after export controls. Thus, export controls counterintuitively made SMIC flush with cash, as controlled Chinese firms in need of chips (like Huawei) and SMIC were driven together, along with the assistance of state funds, procurement contracts, and other central and local government supports.

However, the diversification of these sales was substantially curtailed. Prior to export controls, the share of SMIC sales to Chinese firms was usually in the 40 percent range, with a maximum of 62 percent in 2018Q1. However, after export controls, SMIC's foreign sales precipitously declined as China-oriented sales rose consistently to 75 percent. These sales currently reside above 80 percent. Thus, its contractual orientation has become China-centric and less geographically diversified.

Interestingly, export controls have triggered an enhancement in the sophistication of SMICs sales to Chinese firms. Upon reflection, this may have been expected for similar reasons mentioned, as many major Chinese consumers of semiconductors (like Huawei) have been forced to source chips from Chinese firms. SMIC, as China's leading foundry, would become the primary supplier of more advanced chips, leading its overall portfolio to shift to more sophisticated chips (but still well behind the leading edge). Specifically, SMIC's annual reports show sales in the sub-28nm FinFET category rose from around 5 percent of total sales share to upwards of 30 percent after export controls. However, this category almost certainly includes substantial sales in much more advanced chips in the 14nm to 7nm range, despite not having the most advanced machinery to manufacture these efficiently at scale.

This is because SME is quite different from software. SMEs are physically installed on location and cannot be "cut off" instantaneously. As such, SMIC could milk its installed machinery to work its way down the Moore's law curve. That is, the same machinery that can produce legacy 28nm chips (very efficiently), can also produce more advanced 7nm chips (very inefficiently). What are needed to get less advanced machinery to produce more advanced chips are lots of trial and error and training (or hiring) of engineers to perfect the production craft, as well as a willingness to burn cash on inefficient production. Furthermore, while its R&D expenditure has oddly declined, SMIC has gone on a capex spending spree to purchase SMEs, investing on average 10.7 billion RMB each quarter, compared to only 3.5 billion RMB prior to controls. Similar to above, while these purchases could be used to produce less advanced legacy chips, they most likely will be applied to more advanced chips. This ability to control one's asset makes the job of export control monitoring and the burdens of 'know your customer' much more difficult.

Thus, the technology and its inter-firm linkages have very different implications for export control policy. Chokepoint strength, foreign availability, and high market shares may be necessary preconditions for export controls, but there are many other intervening factors derived from industrial organization. While speculative, it is perhaps these additional factors which drove the Commerce Department to sequentially impose new layers of controls on Chinese firms (three rounds for Huawei, two rounds for SMIC), and then in October 2022 and October 2023 impose China-wide controls.[41]

However, the effectiveness of export controls was questioned by many in September 2023, when (during a China visit by Commerce Secretary Gina Raimondo), Huawei unveiled its new flagship smartphone (Mate 60 Pro) which seemed to defy the American goal of restricting Chinese firms from producing chips below 14nm threshold. The Mate 60 Pro was powered by Huawei's in-house designed Kirin 9000S chip and manufactured by SMIC on a 7nm chip. SMIC was able to do this using older-generation machinery, which surely lowered yields and increased costs. Looking to the future, it is technically possible for SMIC to continue to produce even more advanced 5nm chips using the same older machinery even though yields will decline even further and no foundry has ever attempted this. However, despite the apparent successes in defying US controls within only 2–3 years, it is a pyrrhic victory because this technological trajectory will be a dead-end after 5nm, and it is also commercially unviable, requiring state subsidies and supports to be sustainable. Thus, the longer-term trajectory for SMIC is more grim, and its ability to recalibrate more limited.

Varieties of Ecosystems

Beyond dyadic buyer-supplier ties, firms in many industries engage in complex ecosystems, which pose different opportunities and challenges for export controls. As mentioned, ecosystems are "an interdependent network of self-interested actors jointly creating value." This is a broad definition, and there are many different types of ecosystems. The diversity and complexity of ecosystems makes the work of export controls more difficult.

Some ecosystems, like the Android platforms discussed below, can serve as a very strong chokepoint for US controls, given their network centrality and innumerable complementors and users. However, other ecosystems are not as centralized and are not organized around network effects. These ecosystems are more loosely stitched together through decomposable modules, in which there are multiple and nested layers to the system that resemble 'massive modular ecosystems' (MMEs).[42] As briefly mentioned, modularity is the partial decomposability of a complex system into distinct sub-systems which interoperate through standardized interfaces, and thereby maintain system-level coherence and functionality.

At the core of modularity is the codification of interfaces between specialized modules which allow for extremely complex information to be relatively easily exchanged between modules. Furthermore, higher-level modules can more easily be broken down into smaller sub-modules, allowing firms to become increasingly specialized and thereby creating more complex systems of nested layers—an MME. MMEs are not linear like most GVCs, and thus they belie a sense of hierarchy, centrality, or leadership, which also characterize most GVCs and platforms. An MME contains many nested modules, each with its own set of firms and dynamics. Modules (and the firms building them) are only loosely coupled, meaning that the dependencies between modules are attenuated, so firms are interlinked but act separately and are less organizationally integrated.

This industry organization makes sanction enforcement uneven and more unpredictable. For instance, a single module may appear to be a classic chokepoint, with very high market and country concentrations, and it may also be broadly interconnected in the MME, mimicking network centrality. However, as illustrated below, even when modules have similarities in their *formal network structures*, modules of an MME differ in terms of how they are linked to each other and the opportunities for sanctioned firms to 'escape' sanctions by pursuing alternative innovation trajectories, whether through adjacent MMEs or moving up or down the nested layers. In some cases, seemingly secure chokepoints are purely 'mirages,' as targeted firms and countries have multiple means to achieve their desired ends. In other cases, modules are truly chokepoints because they cultivate network effects and interlink across multiple layers and other nodes, such as the example of the Android OS platform which integrates across many system-level functions.

The remainder of this section demonstrates how some ecosystems can serve as very powerful chokepoints that improve export control effectiveness, using Android OS as an example. It then considers the opposite—the many ways that ecosystems allow substantial flexibility to Chinese firms, beyond the two primary pathways studied by most analysts, namely 'workarounds' and 'catchup.'

Strong Ecosystem Chokepoint: Android OS

We begin with Android, the Google OS platform mentioned earlier, which is a strong chokepoint in its ecosystem. Because it is a genuine platform—a type of ecosystem—it is truly indispensable and incredibly hard to replace. It is well-known that starting in 2009, with the blocking of YouTube in China, Google's wide range of products were gradually degraded, hacked, or outright blocked in China. By mid-2014, nearly all Google products were essentially inoperable in China, including Gmail, the Google Play mobile apps market, Google Drive, cloud services, maps, and basic account login, among others. Most of these are also considered platforms but proved replaceable in China.

Yet, despite this near absolute exclusion, another Google product—the Android OS—paradoxically remains nearly ubiquitous in China today, installed on 78 percent of all mobile devices, which accounts for nearly all non-Apple mobile device (iOS accounts for 21 percent).[43] Android is an open-source operating system, which China's largest smartphone companies (Oppo, Vivo, Xiaomi, and even Huawei) can freely utilize and customize (called 'skins') using an open-source license.

Despite the 'openness' of Android, it has national security implications when export controls were placed on Huawei, because Google was required to withhold its regular software updates that over time slowly degraded all existing Huawei phones. Furthermore, while the OS is open-source, Google's many proprietary products (Google maps, Google Play, YouTube, etc.) were also restricted on Huawei phones—not just in China but worldwide—thus making Huawei phones unattractive outside of China.[44] Some argued that among all US technologies denied to Huawei, the loss of Google products was the most damaging and hardest to overcome.[45] This is due to its *organizational* form as a platform.

However, in June 2021 and to much fanfare in China, Huawei released its own operating system, HarmonyOS (*hongmeng*). It triumphantly announced that it was "a milestone." Huawei's head of software, Chenglu Wang, declared that it was "neither a copy of Android nor [Apple's] iOS." Even Huawei founder and CEO, Zhengfei Ren declared, "in the software domain, the US will have very little control over our future development, and we have much more autonomy."[46] However, software engineers who explored Harmony OS after its release concluded that "HarmonyOS was identical to what Huawei ships on its Android phones, save for a few changes to the 'about' screen that swapped out the words 'Android' and 'EMUI (Huawei's Android skin) for 'HarmonyOS.'"[47]

Thus, despite attempts to completely purge China of Google products, some products like Android are seemingly impossible to uproot, even for a technological powerhouse with strong software expertise, like Huawei, and with coordinated central government efforts. This year, Huawei will release another version, called HarmonyOS NEXT, which they claim will be purged of Android code base.

Android's indispensability is because it is a multi-tiered platform which is extremely difficult to substitute due to its powerful network effects. These are generated by its millions of complementors and users, who collectively reinforce its global dominance and make it irreplaceable. Even compared to other platforms, Android is particularly indispensable because of its 'location' in the broader ICT stack, which crosses multiple parts of the digital stack.

Loose Coupling in Massive Modular Ecosystems

As discussed, MMEs stress the decomposability of modules, which allows for more complex multi-layered industry organization. They also emphasize the adjacency of products and industries, and the instability and uncertainty of innovation and technological evolution. Thus, when applied to US export controls and Chinese counter-strategies, the range of possible counter-strategies is far broader.

As discussed below, a non-exhaustive list of Chinese counter-strategies to export controls include:

1. Product redesigns through product architecture innovations

2. Moving between MME layers to achieve the same goals through new product innovations.

3. Replacing critical platforms through open-source software, which maintains the benefits of interdependence.

4. Entering adjacent industries by repurposing existing resources, capabilities, and talent.

Of course, it is exceedingly difficult to definitively 'map' an MME and so predicting counter-strategies and future technological trajectories is partly conjectural. This reflects the nature of an MME itself. However, the conceptualization has theoretical and practical implications, because it raises questions about our fundamental understanding of industry organization, and the implications for policy. How does this impact assessments of export controls?

As American export controls expanded and diversified, the assessments of analysts broadly remained within the confines of classic export controls, consisting of myriad variations on one of two themes: modest 'workarounds' by Chinese firms to evade American export controls, or more radical ideas of 'catchup' by Chinese firms. Of course, specific assessments evolved with the expansion of US controls, thus one must be very precise with event dates, so as not to misjudge earlier assessments of 'workarounds' or 'catchup' based on later export control alterations. Furthermore, it should be reiterated that none of these assessments are wrong, but their usefulness are confined to their particular conceptualization of industry organization. After summarizing assessments of workarounds and catchup, the paper returns to the four additional pathways that MMEs open up for Chinese firms.

Chinese Workarounds

Many analysts rightfully predicted that Chinese companies would attempt to evade American chokepoints by engaging in various types of illegal deceptions.[48] For instance, given American network centrality in EDA software, HiSilicon's (Huawei's chip design house) primary short-term option was to pirate new EDA software. After the August 2020 FDPR extension, analysts understood that this workaround was largely cutoff because chip designs using American EDA tools would not be manufacturable given TSMC's (the world's largest chip foundry) reliance on US-origin technologies and its network centrality in manufacturing the most advanced chip nodes.

However, even without the broader extraterritorial controls on manufacturing, pirating EDA software would prove difficult on its own. This is because of broader network linkages, unrelated to Huawei. Unlike conventional software, which is relatively static after purchase, EDA software is constantly updated, especially for leading edge designs, because foundries must update their hundreds of process design kits (PDKs), sometimes monthly for the leading-edge.

PDKs are released by foundries and ensure that designs are simulated using the latest upgrades at the foundry. PDKs are integrated into EDA software, and so when updated, the foundry authenticates the EDA license. Thus, if Huawei were to design new chips on pirated software, the engineering hours put into the new designs would become obsolete once a new PDK was released. They would have to re-pirate and then re-design their chips accordingly. Since this happens regularly, the nature of the software and its 'location' in the broader ecosystem makes pirating unfeasible.

Under these new export control conditions, and to circumvent controls on actual chips, Chinese firms were also predicted to establish shell companies through which controlled items could be transshipped to China.[49] Alternatively, these firms could establish legally distinct but clearly integrated companies to engage in chip manufacturing, such as Huawei-funded Pengxinwei IC manufacturing, which imported equipment that controlled Chinese firms could not.[50] American companies under US controls also chaffed at the controls, and some reports indicated that they may have been engaged in both legal and legally gray workarounds that tested BIS rulings. It is well-known that Nvidia re-designed their A-100 chips in order to fall just under the legal threshold to sell to Chinese firms—a pathway that the Commerce Department quickly foreclosed.[51]

Others are less well known. For instance, one particularly well-informed analyst reported that KLA (a major US SME firm) stated in its earnings calls that it was considering plans to de-Americanize its own (American) equipment to escape American extra-territoriality.[52] The same analyst found that a Chinese JV partner of Synopsys (one of the three dominant American EDA software firms) was under investigation by the Commerce Department for giving Huawei access to controlled software.[53] Others have proffered that Chinese multinationals with subsidiaries in third-countries could purchase as many controlled items as they wished because US export controls do not apply to a company's country of ownership. The illegal transaction would only happen when the subsidiary sought to transfer these controlled items into China proper.[54]

Apart from Chinese firms, their subsidiaries, or shell companies, other possibilities include foreign firms aiding Chinese workarounds. For example, foreign companies could also work towards de-Americanizing their products. It was predicted that some firms in Japan and Europe, were already de-Americanized. Although these pathways were more likely to succeed prior to the October 2022 controls, at the time, analysts warned that "non-American companies make great chips, too," allowing Huawei to swap out US chips.[55] Even after the imposition of FDPR on machinery, Japanese and Dutch SME companies were "suddenly much more attractive suppliers" to the Chinese, since they were deemed to not rely on US technology or could more easily de-Americanize their products.[56] This raised the importance for American diplomats to multilateralize controls with key countries like Japan and Netherlands.[57]

All of these predictions are variations on the same theme of 'workarounds' to overcome a handful of American chokepoints in a linear semiconductor GVC. In total, they constitute a mountain of headaches to successfully enforce American export controls, which is why, as American officials learned more, the controls progressively expanded after 2019.

Chinese Catch-up

At the other end of the spectrum are bold predictions that China could 'catchup' technologically, or even achieve 'self-reliance.' Many analysts expressed pessimism about American controls, not because of ineffective enforcement (workarounds), but because they would stimulate Chinese policymakers and firms to double down on self-reliance. While China has long talked of technological self-reliance, the ease and affordability of relying on American technology offered few incentives. Now, it was argued, the Chinese would become single-minded in fulfilling their techno-nationalist dreams, as business and government were thrown into each other's arms.[58]

Innumerable media articles since 2019 reported on new Chinese investments, initiatives, and subsidies being thrown into advancing Chinese semiconductor tools, equipment, and software by Huawei, the local Shenzhen government, and Beijing,[59] declaring that "China threw even more money at its already heavily subsidized chipmakers."[60] What is more, in many reports, Chinese firms truly appeared to be achieving catchup, almost miraculously fast.

As already mentioned, Huawei (falsely) reported that its HarmonyOS (*hongmeng*) had displaced Google Android within a year of export controls, though it still hit global media. Similar reports appeared of Huawei phones quickly being de-Americanized of chips,[61] as well as Huawei's telecom base stations.[62] Some analysts observed that this sort of reporting accelerated American decisions to impose the October 2022 export controls. For instance, Chinese leading memory manufacturer, YMTC, seemingly surpassed market leaders Samsung and SK Hynix, when it began shipping 232-layer memory chips and became an Apple supplier.[63] As discussed, China's leading foundry, SMIC, announced it had produced 7nm logic chips in July 2022, using SMEs that were one generation older than the leading edge.[64] Elsewhere, Chinese leading AI chip designer, Biren, released chips that approximated the capabilities of Nvidia's advanced A100 GPUs.[65]

Altogether, these reports portrayed China as a technological juggernaut that could make export controls meaningless, simply by overcoming US chokepoints through replication. Even for the advances that proved true, smart analysts understood that Chinese accomplishments still remained reliant on foreign technology. For instance, advanced chips relied on design and manufacturing tools, as well as IP that were overwhelmingly not Chinese. Thus, given the complexity of MMEs, catchphrases like 'catchup' and 'self-reliance' are hard to define. Nevertheless, in nearly all of these assessments, analysts focused on the viability of the American chokepoints targeted by the Commerce Department; and, they largely focused on particular semiconductors product categories, assuming that the GVC is linear.

MMEs and Chinese Counter-strategies

Using the lens of MMEs, export controls look quite different. The logic of BIS has broadly been to create enforcement chokepoints at key nodes along linear GVCs, especially focused on semiconductors. Even the logic of the most expansive October 2022 export controls rests upon a linear supply chain and a focus on several chokepoints where US firms appear to possess chokepoint strength. The ultimate goal of these controls is to restrict Chinese access to high-performance computing (HPC) capabilities which can be used to train advanced AI models and can be applied to military applications, like hypersonic aerospace, nuclear, and other advanced military applications.

The pathway to achieve this goal is not simply by restricting the end-use of HPC and AI, but also to restrict the upstream hardware that goes into these. Going back along a linear semiconductor GVC, this includes very specific classifications of the most leading-edge logic, memory, and GPU chips, then any components or inputs which may advance China's own SME sector which could allow for indigenization of SME tools, and finally even American nationals who are necessary to install and continually service SMEs in China. The ultimate goal of export controls is not to deny China access to leading-edge semiconductors. Rather, the ultimate goal is restricting a company on the Entity List or some sort of final end-product for an end-use (e.g. military modernization), whether it is Huawei telecom equipment, Hikvision advanced cameras, or HPC capabilities, in the case of the October controls. Semiconductors and SMEs are simply convenient chokepoints of enforcement for these other goals.

However, given the nested layering of MMEs, the degrees of freedom are much greater than implied by a linear GVC with chokepoints. MMEs offer substantial flexibility for innovation, which in some cases can undercut chokepoints that initially appear strong. Although there are not crystal clear lines differentiating the following counter-strategies, this paper examines four:

1. Product architecture redesign.

2. Shifting MME layers to generate different products but achieving the same technological goals.

3. Innovating on new open-source platforms.

4. Repurposing the same resources, capabilities, and talent to enter new industries.

Counter-strategy 1: Final Product Redesign

The first pathway to avoid the chokepoints of advanced node semiconductors is redesigning final products by utilizing less advanced chip technology. For instance, it has been suggested that Huawei's 5G base stations could be redesigned using less advanced 28nm chips, rather than more advanced 14nm node chips through software and system redesign.[66]

Part of this innovation may also involve shifting between layers (see below). For instance, Huawei's chip design house, HiSilicon, has also redesigned its telecom equipment and automotive chips so that they can be produced on older SME technologies, which are already installed and used in Chinese chip making companies, like Fujian Jinhua Integrated Circuit Co. (JHICC) and Ningbo Semiconductor International, both also on Commerce's Entity List.

Software redesign has been used in contexts outside of export controls. For instance, although not an example involving China, during the height of the chip shortage that impacted the American automobile industry, Tesla reported to its shareholders that "within weeks," it had rewritten substantial portions of its firmware (software code) so that it could utilize chips that were in greater abundance, even sourcing them from brand new suppliers.[67] Thus, as a general rule, many products can be redesigned and re-architected to use simpler components, but still end up with an equivalent end-product with equivalent performance. Thus, in this pathway, one ends up with the same basic product and performance, but through a different design. While the distinctions may be blurry at times, this differs from the prior discussion in which Huawei de-Americanized its products, by simply using foreign suppliers who could provide comparable, de-Americanized products.[68]

Counter-strategy 2: Shifting MME Layers

A second pathway is to shift layers in the MME to achieve the same end goal, but through different product combinations. For instance, the October 2022 export controls aimed to cut China off from HPC, which could be used to train large AI models for military purposes. However, the export controls assume that China can only tap into HPC within its own borders and only by direct purchasing of leading-edge node GPUs from companies like Nvidia.

However, if Chinese firms or state institutions moved 'up' the digital stack to cloud computing, there is quite a different geography than the export controls envision. For instance, large Chinese AI models could be trained in data centers outside of China. Assuming Chinese organizations do not want to create new dependencies on American cloud services, Alibaba, Tencent, and increasingly Huawei have built data centers outside of China. Export controls do not restrict controlled items based on the country of ownership but rather only the location of the facility itself. For instance, Huawei has installed at least 70 data centers and other cloud services around the world.[69]

Although these are mostly supplied to foreign governments, there is little reason to believe that Chinese cloud companies could not set up advanced data centers outside of China to train next-generation AI models. Under current American export regulation, they could even purchase as many of the most advanced chips to accomplish this, as long as the data centers remained outside of China. Even for data centers within China, there could be ways of architecting them to avoid export controls. For instance, to achieve similar compute capabilities but avoid the chokepoint of leading-edge chips, Chinese cloud companies could design more customized and hence efficient chips (customized ASICs instead of GPUs),[70] while also interconnecting more but simpler chips together. This is more costly and less efficient at the system-level, but could be effective to achieve their ends. Other avenues might include advanced packaging of chips.

Counter-strategy 3: Open-source

A more significant pathway to evade semiconductor controls deep in the ICT stack is developing open-source software, and major Chinese firms appear to be pushing forward on this (see Atom Foundation). One example of this is RISC-V architecture for the underlying instruction set for semiconductors, something which will become increasingly attractive to Chinese companies, as they are outside the scope of export controls. Chinese firms seem to be pushing forward on RISC-V along many fronts: nearly half of the premier members of the RISC-V Foundation are Chinese;[71] Alibaba and Tencent have spearheaded a Chinese RISC-V consortium under government guidance;[72] hundreds of Chinese firms are working on RISC-V in China;[73] and local governments like Shenzhen are offering subsidies to local firms using RISC-V.[74] Even the RISC-V Foundation has taken precautions against the possibility of US sanctions by shifting its headquarters to Switzerland from the United States.

Beyond RISC-V, open-source in general is attractive to China to avoid US controls at multiple levels of the MME. For instance, Huawei is investing across many aspects of open-source, and it is taking precautionary measures like moving its code to Chinese Gitee, rather than Microsoft-managed GitHub.[75] They also have opened up source code and compilers to encourage their own ecosystems. It is hard to know where all of this will lead, and there currently are many limitations to open RISC-V and open-source in general.[76]

However, the larger point is that the export controls are stimulating innovations in open-source spaces which were previously less significant. Furthermore, as platforms, their major barrier to growth is achieving the necessary momentum among users in order to scale, and to achieve a certain threshold of usage and demand, which then creates a cascade effect of users that collectively can solve many of the open-source problems. Export controls may unite a large segment of Chinese firms and software talent around open-source platforms, giving them the momentum they need.

Counter-strategy 4: Repurposing Resources to New Products

Finally, resources, talent and capabilities can be more easily repurposed across adjacent industries within MMEs. Part of this is because of many more generalized skills and resources that can apply across MMEs, such as software languages, and some libraries, compilers, debuggers, and other tools. In this sense, export controls could induce Chinese resources to be redeployed to adjacent industries. We already discussed how Chinese firms have multiple routes to acquire HPC by moving up the MME layers to cloud computing. But, cloud computing is also an avenue for Chinese firms to repurpose resources to enter a new industry, as Huawei has done to replace lost revenues in smartphones. This repurposing makes sense for Huawei because telecommunications and cloud computing are increasingly merging as more telecommunication network operators utilize the cloud service providers to run even their core networks, including major ones like AT&T.[77] Given international concerns of Huawei telecommunication equipment, its entry into cloud computing seems to be a natural extension of its core competencies.

Similarly, China's semiconductor capabilities are being forced to redirect towards less sophisticated nodes, like 28nm and higher, where innovation on design (China's relative strength) will be more important than manufacturing innovations. This might redirect talent and resources to a host of industries that have potential military and security implications, such as IoT, swarm military technologies, robotics, and edge computing.

Of course, new industries can be built in any industrial sector. However, MMEs have special qualities based on modularity and standardized interfaces, which allow for greater flexibility, and the ability to innovate rapidly and experimentally through recombining components, resources, talent, and capabilities. While chokepoints do exist in certain nodes in the MME, there are many pathways to make the same product (e.g. base stations), achieve certain desired ends (e.g. HPC), or to redeploy resources to new products and sectors with military applications (e.g. swarm).

Conclusion

In recent years, the Commerce Department has returned to a Cold War-like strategy of controlling dual-use American technologies to degrade the military capabilities of a rival. However, today's industrial organization has little resemblance to the Cold War era. This poses new challenges for policymakers. Today's dual-use technologies are overwhelmingly commercial in use and produced by commercial firms. Furthermore, innovations in advanced technologies require the combined expertise of many specialized firms that must more openly share knowledge and resources than in prior industrial eras.

In important ways, the new industrial organization subtly alters some principles and assessments of classic export controls. While chokepoint strength (such as the degree of foreign availability') is still important, American coercive potential cannot be measured based on US firms' market share. From the perspective of classic export controls, it may appear that US firms dominate key product categories, thereby offering policy makers clear chokepoints. However, some of these high market-share chokepoints may be 'mirages' given the highly flexible nature of business ecosystems that readily allow for multiple pathways to achieve the same product or strategic goals.

Under these conditions, export controls will fail, and possibly even induce new pathways of Chinese innovation. Mirage chokepoints, in which American market concentration appears substantial, can also make policymakers overconfident in American coercive power, thus encouraging policymakers to be more unilateral and more extraterritorial, as well as lead them to make overly narrow assessments of Chinese counter-strategies.

In most cases, assessments of China's options under export controls boil down to two basic trajectories: Chinese 'workarounds' or Chinese technological 'catch up.' Neither of these assessments is wrong, as Chinese firms and state actors have engaged in both counter-strategies. However, in both scenarios, it is assumed that the controlled technology is essential for Chinese progress in technological innovation, giving the impression of unilinear technological change, which foregrounds the assumed chokepoint. However, given the flexibility of industrial ecosystems and the variety of ways that firms exchange resources, technologies advance in more multilinear ways, and it is rare to find true chokepoint strength. As such, policymakers need to consider a broader palette of factors that contribute to policy effectiveness on targeted firms and countries, as well as more complex and varied second and third-order effects on American and allied firms.

Notes

1. I use the broader term 'value chain' rather than 'supply chain.' Supply chain research focuses on the efficient logistical flow of tangible goods. Value chain research is broader as it incorporates supply chains, but also includes intangibles like intellectual property and standard-setting, and services like business functions outsourcing, among others (Park, et al 2013).
2. Antony Blinken, "Remarks to the Press" at Stanford University, October 17th, 2022 https://www.state.gov/secretary-antony-blinken-remarks-to-the-press-3/
3. The China threat is one of the few areas of bipartisan agreement in US politics, evidenced by the institutionalization of the conflict, such as the House Select Committee, the State Department's China House, CIA's China Mission, China policy in the annual National Defense Authorization Act, etc. Similarly, Xi Jinping has propagated equally anti-American rhetoric (wolf warriors) and institutionalized conflict with the West, including through new military-civil fusion policies (2017), its comprehensive national security state (2013), and a series of new policies, including building its own export control and sanctioning regimes.
4. Jake Sullivan, "Remarks by National Security Advisor Jake Sullivan on Renewing American Economic Leadership at the Brookings Institution," White House, April 27th, 2023 https://www.whitehouse.gov/briefing-room/speeches-remarks/2023/04/27/remarks-by-national-security-advisor-jake-sullivan-on-renewing-american-economic-leadership-at-the-brookings-institution/
5. Author's data, accessed on July 23, 2023.
6. Homer O. Blair, "Export Controls on Nonmilitary Goods and Technology: Are We Penalizing the Soviets or Ourselves?" Texas International Law Journal 21, no. 2 (1986): 363–372; Tim Hwang and Emily S. Weinstein, "Decoupling in Strategic Technologies" (Center for Strategic and Emerging Technologies, 2022); Tongele, "Emerging and Foundational Technology Controls" (Washington, DC: US Department of Commerce, 2022).
7. *Inter alia*, see Henry Farrell and Abraham L. Newman, "Weaponized Interdependence: How Global Economic Networks Shape State Coercion," International Security 44, no. 1 (2019): 42–79; Henry Farrell and Abraham Newman, Underground Empire: How America Weaponized the World Economy (New York: Henry Holt and Company, 2023); David Singh Grewal, Network Power: The Social Dynamics of Globalization (New Haven: Yale University Press, 2008); Mark Leonard, "Connectivity Wars: Why Migration, Finance and Trade Are the Geo-economic Battlegrounds of the Future," European Council on Foreign Affairs 13, no. 27 (2016); Thomas Oatley, "Weaponizing International Financial Interdependence," in The Uses and Abuses of Weaponized Interdependence, ed. Daniel Drezner, Henry Farrell, and Abraham Newman (Washington, DC: Brookings Institution Press, 2021), 115–130; Tobias Roth et al., "Critical Technology Supply Chains in the Asia-Pacific: Options for the United States to De-risk and Diversify" (Washington, DC: National Bureau of Asian Research, 2023); Juan Zarate, Treasury's War: The Unleashing of a New Era of Financial Warfare (New York: Hachette UK, 2013).
8. Daniel Drezner, "Introduction," in The Uses and Abuses of Weaponized Interdependence, ed. Daniel Drezner, Henry Farrell, and Abraham L. Newman (Washington, D.C.: Brookings Institution Press, 2021).

9. Gary Clyde Hufbauer et al., Economic Sanctions Reconsidered, 3rd ed. (Washington, DC: Peterson Institute for International Economics, 2008), pp.175.
10. Hufbauer et al., Economic Sanctions Reconsidered, pp. 209.
11. Kevin Wolf, "Advancing National Security and Foreign Policy Through Sanctions, Export Controls, and Other Economic Tools" (testimony before the Senate Committee on Banking, Housing, and Urban Affairs, Washington, DC, 2023).
12. Hwang and Weinstein, "Decoupling in Strategic Technologies."
13. Section 4811(5) states "Export controls should be coordinated with the multilateral export control regimes. Export controls that are multilateral are most effective." And Section 4811(6) states "Export controls applied unilaterally to items widely available from foreign sources generally are less effective in preventing end-users from acquiring those items. Application of unilateral export controls should be limited for purposes of protecting specific United States national security and foreign policy interests." See https://uscode.house.gov/view.xhtml?req=(title:50%20section:4811%20edition:prelim)
14. See Assistant Secretary Kendler's remarks to European allies. https://www.bis.doc.gov/index.php/documents/about-bis/newsroom/press-releases/2941-2022-03-30-bis-press-release-aci-12th-cloud-encryption-and-cyber-conference-as-kendler/file
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39. For instance, by designing one's own chips, Huawei could better design its system-level products (e.g. base stations, smartphones) to its own chips. Apple and Samsung are the only other firms that do the same at scale in smartphones. But, there is a degree of lock-in. Of course, the export controls cut off both EDA tools (for internal designs) and third-party chips, so both avenues for chip acquisition. On the enforcement side, however, while controversial, it is arguably easier to enforce EDA software restrictions given that there are only three major suppliers and they are all American, whereas many non-American firms design chips, so the key chokepoint is manufacturing leading-edge chips through TSMC. TSMC is not American (though they comply to US export controls) and they produce for many companies, so there are many more avenues by which chips can flow to controlled Chinese companies.
40. Another rough proxy of a shift in strategy for Huawei is a word count for "software" in its annual reports (Huawei is not publicly listed, however). Between 2013 and 2018, "software" appears 38 times on average, whereas from 2020 to 2023, this jumps to 91 times, even though their annual reports only lengthened (in page numbers) by 25 percent between these periods. The transitional year 2019 had 65 appearances.
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