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Securing Semiconductor Supply Chains

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Executive Summary

The United States and a small number of democratic allies dominate supply chains producing advanced computer chips, but this advantage could erode without new, targeted policies. Advanced computer chips underpin virtually all important technology today. China is investing heavily in becoming a new center of gravity in chip production and could succeed in developing state-of-the-art capabilities.

The United States and its allies should undercut China's efforts with "protect" and "promote" policies aimed at improving supply chain security and maintaining China's dependence on the United States and its allies for imports of advanced chips—especially state-of-the-art logic chips, which perform calculations that power advanced applications like artificial intelligence. By controlling the production of advanced chips, the United States and allied democracies can ensure that these technologies are developed and deployed safely and ethically to broadly benefit the world.

To **protect**, they should limit China's access to key supply chain inputs with export and investment controls and challenge China's market-distorting state subsidies. To **promote**, they should fund research and development, create financial incentives, develop and retain top talent, and reduce unnecessary trade barriers.

Advanced chip supply chains are among the world's most complex and globalized. Their globalization sustains innovation by bringing together worldwide resources and talent pools. Indigenizing the entire supply chain for producing advanced chips would prove incredibly difficult and costly for any country, including the United States. But together, the United States and its allies—above all, Japan, the Netherlands, Taiwan, South Korea, the United Kingdom, and Germany—enjoy a competitive advantage at nearly every step of the supply chain needed to produce these chips.

Historically left out of advanced segments of these supply chains, China seeks to join semiconductor leaders. China is lavishing unprecedented subsidies on its semiconductor industry to indigenize its supply chains. It heavily subsidizes chip design firms and chip factories ("fabs") turning their designs into chips. Together, these efforts have given China local chip production capabilities—albeit several generations behind the state of the art.

China’s efforts pose risks to national and international security. First, China’s subsidies could provide an independent ability to manufacture state-of-the-art chips. Underpinning all industry, the information economy, and military power, these chips are especially necessary for many emerging technologies, such as artificial intelligence. China could then deploy these technologies in dangerous and destabilizing ways (e.g., by starting arms races) or violate human rights and democratic values (e.g., by enhancing surveillance and other authoritarianism friendly technologies). Second, rising costs, economies of scale, and the clustering of know-how allow only small numbers of semiconductor firms to profitably operate at the state of the art. China’s success in developing state-of-the-art firms could displace leading U.S. and allied semiconductor firms, thereby harming their countries’ supply chain security.

The United States and its allies should protect national and international security by maintaining China’s advanced chip dependence and retaining key supply chain sectors on friendly shores. China’s subsidies to its chip designers and factories fund purchases of foreign inputs from the United States and its allies, including advanced semiconductor manufacturing equipment (SME), advanced materials, electronic design automation (EDA) software, and licenses to chip design intellectual property (IP). These elements are “chokepoints” in China’s chip supply chains: necessary to produce advanced chips, and for now, only available from the United States and its allies. Such chokepoints, described in detail in a companion CSET report,[1] present a policy opportunity. To ensure China cannot build local capacity against market forces, and instead fortify that capacity in the United States and allied democracies, these countries should:

- **Apply export controls on chokepoints.** The United States and its allies should control, with presumptive denial of licenses, advanced SME (especially extreme ultraviolet (EUV) photolithography and argon fluoride (ArF) immersion photolithography tools), advanced materials (photomasks and photoresists), and software necessary for China to build and use advanced chip factories. Or, as a backup option, they can consider limited controls on EDA software (for chip design) and intellectual property to slow improvement in China's chip design capabilities. These controls would ensure China’s dependence on imports for advanced chips.

- Then, the United States and its allies should monitor exports of (and as necessary, apply targeted export controls, such as end-use and end-user controls on) advanced chips underpinning dangerous or human-rights violating compute-intensive technologies particularly relevant for Chinese state actors. These could include military AI systems, cryptography, the design of nuclear weapons, and AI-enabled surveillance systems. However, the United States and its allies should broadly permit chip exports to China for peaceful, commercial uses and avoid unilateral controls when alternative suppliers exist.
- See Figure 1 for a flowchart-style decision tree describing how the United States can navigate these controls.

Five other policies stand on their own but also increase the effectiveness of export controls. Specifically, the United States and allied democracies should:

- **Fund public-private partnerships.** The United States should pursue additional public R&D funding in partnership with industry. This funding would consolidate and extend the U.S. and allied lead in semiconductors, compensate firms impacted by export controls, and convince allies to collaborate on them. The United States should also provide financial incentives to chipmakers building leading-edge chip factories in the United States.
- **Reduce unnecessary trade barriers.** The United States and its allies should reduce industry-harming trade barriers, including economically motivated import tariffs and overbroad or unilateral export controls. These measures would strengthen the U.S. and allied semiconductor industries, which rely on global supply chains.
- **Challenge Chinese state subsidies for semiconductors.** China's subsidies distort global semiconductor markets, making them more brittle and taking global market share from the United States and allied democracies against market forces. Both of these trends threaten the U.S. and allied semiconductor industries. These countries should challenge China's subsidies through trade negotiations (using reduced export controls as a bargaining chip) or at the World Trade Organization.
- **Develop and retain access to top talent.** Maintaining the U.S. semiconductor industry's competitiveness and drawing supply chains to U.S. shores requires access to top talent. The United States should invest in research and education, sustain and improve aspects of the

U.S. immigration system, and revise deemed export controls to ensure foreign nationals can work in the U.S. semiconductor industry, rather than being driven away to competitors' industries.

- **Screen investments to reduce technology transfer.** Chinese entities and other competitors gain access to semiconductor technology through IP licensing, investment, and mergers and acquisitions. The United States and its allies should more thoroughly regulate these pathways to prevent unwanted technology transfer.

Introduction

The United States and a small number of democratic allies—especially Japan, the Netherlands, Taiwan, and South Korea—control supply chains that produce advanced chips. These supply chains involve more than 1,000 steps passing through numerous countries. Distilled to their essence, they include the following high-level categories: basic research; the production of electronic design automation (EDA) software and intellectual property (IP) used to design chips; chip design using EDA; the production of semiconductor manufacturing equipment; the procurement and processing of materials such as silicon; the manufacture of chips in fabs based on chip designs using SME; the assembly, testing, and packaging of manufactured chips using SME; and distribution and end-use of chips.[2]

Seeking to join this club and displace its members, China is heavily subsidizing its semiconductor industry. It has achieved less advanced local chip production capabilities—including a small amount of "14 nm" production, which is three generations and six years behind state-of-the-art "5 nm" technology. But with concerted efforts, China could achieve state-of-the-art fabs. The country is also rapidly expanding its share of the world's chip production capacity—moving from a negligible share in 2000 to 20 percent in 2020, with a further increase projected by 2030. (More than 40 percent of China's current chip production capacity is owned by foreign companies.)[3] Given the importance of advanced chips to high technology, China's efforts pose risks to national and international security.

The next section of the paper develops proposed policy aims and explains why these are appropriate strategic-level goals that should guide thinking on U.S. semiconductor supply chain policies. These aims seek to:

- **Maintain China's chip dependence** on the United States and its allies, providing leverage over China's uses of advanced chips that harm international security and human rights.
- **Keep supply chains in the United States and allied democracies** to ensure reliable access to chips free from tampering.

The following section then surveys the semiconductor supply chain and highlights key "chokepoints" in China's chip supply chains,[4] the elements necessary for advanced chip production exclusively produced by the United States and its allies: advanced SME, materials, EDA software, and licenses to advanced chip design IP. A companion CSET report describes these chokepoints in more detail.[5] The section also develops a flowchart-style decision tree for how the United States can leverage those opportunities. In particular, export controls can achieve **three goals** to support the policy aims above:

- Controls on certain advanced SME (especially advanced photolithography tools), materials, and EDA software can **slow China's ability to build or use advanced chip factories**.
- If the above controls are ineffective, controls on EDA software and IP could **slow China's chip design capabilities**.
- Any of the controls in the first two bullets could maintain China's dependence on imports for advanced chips. If they succeed, the United States and its allies should apply targeted **export controls on advanced chips**—with direct controls on chips, controls on re-exports of chips, and controls on large cloud computing purchases—to prevent uses that harm international security or human rights.

The report then describes five related, stand-alone policies that would increase the effectiveness of export controls if simultaneously implemented:

- **Fund public-private partnerships** on R&D to bolster the U.S. and allied semiconductor industries, particularly in sectors impacted by export controls, and provide financial incentives for leading-edge U.S. fab construction.
- **Reduce unnecessary trade barriers**, including economically motivated tariffs and overbroad or unilateral export controls on commercial chips.
- **Negotiate with or push China** to drop its market-distorting semiconductor subsidies.
- **Ensure access to top talent** to maintain U.S. industry competitiveness and to support local consolidation of chip supply chains.
- **Screen investments to combat technology transfer** by vetting Chinese investment in critical U.S. and allied semiconductor technologies.

The report closes with a discussion of China's potential responses to the types of export control options suggested in this report. Appendices contain data supporting the main sections of the report.

Policy Aims

This report focuses its policy options on two aims. The first is to achieve security benefits from China's reliance on chip imports by limiting its domestic advanced chip design or manufacturing capabilities. The second aim is for the United States and allied democracies to ensure security of their supply chains by controlling key segments.

Security Benefits from China's Chip Dependence

Continued Chinese reliance on the United States and allied democracies for state-of-the-art computer chips benefits U.S. national and international security. If China remains reliant, these democracies should apply targeted export controls to ensure no Chinese entities engage in advanced computer chip uses that are dangerous, destabilizing, or that violate human rights and democratic values. Currently, China imports most of the chips it uses, but aims to build more local chip design and production capacity.[6] Yet this effort relies on foreign inputs that the United States and its allies can limit or block.

Today, China manufactures only a minority of chips consumed in the country.[7] The chips it manufactures use older technology and are less cost-effective than their leading-edge counterparts.[8] To build local chip production capacity, China gives its semiconductor industry $15 billion a year in subsidies.[9]

China's ambitions focus on indigenizing chip design and fabrication. It focused an initial $12.7 billion of subsidies on chip designers (17 percent of total subsidies) and fabs (65 percent). Only 8 percent was allocated to SME and materials, and less to EDA software.[10] Therefore, even if its other indigizenation efforts succeed, China will likely continue to rely on foreign EDA software for chip design, licenses to foreign design IP, and foreign SME and materials for chip fabrication.

Limiting China's access to these foreign inputs through export controls and other policies would perpetuate its dependence on the United States and its allies. Without SME and materials, China cannot indigenize chip fabrication and must rely on chip imports. Similarly, without design IP and EDA software, China cannot indigenize chip design and will require foreign chip designs, even for chips manufactured locally. An inability to design advanced chips would also reduce demand for China’s domestic fabs, which depend on business from Chinese fabless designers.

The United States and its allies should seize upon China’s design and fabrication reliance to apply targeted export controls, ensuring the country uses chips in ways consistent with U.S., allied, and global security. The cost-effective development and deployment of most emerging technologies and advanced weapons systems require state-of-the-art chips. Technologies benefiting from state-of-the-art chips include artificial intelligence, 5G, autonomous drones, cryptography, hypersonics, and nuclear weapons.[11] To slow Chinese state development of these technologies, the United States and its allies should apply end-user export controls on Chinese state actors (e.g., the military), supercomputing entities, or private actors with close ties to the Chinese government. Additionally, they should apply end-use export controls to ensure no Chinese entities gain access to advanced chips for compute-intensive technologies presenting risks to human rights or international security, such as those listed above.

Supply Chain Security

With a combination of “promote” and “protect” policies, the United States and its allies should keep state-of-the-art chip production on their shores. Maintaining indigenous production capacity would ensure the U.S. government and chip designers can outsource fabrication to domestic fabs, rather than relying on foreign fabs potentially less reliable in a crisis. Moreover, outsourcing fabrication increases risks of tampered chips with backdoors for surveillance or disruption by foreign governments. Yet the U.S. share in leading-edge capacity is declining and could disappear entirely.

Countering China's subsidies aimed at indigenizing chip design and production would increase supply chain security by ensuring China cannot displace U.S. and allied design and production. The United States and its allies should use "promote" policies like tax incentives and R&D funding, and "protect" policies such as challenges to China's subsidies and export controls on SME, EDA, materials, and chip design IP. Global chip demand, and to a lesser degree global demand for custom chip designs, are independent of where chips are designed or produced. Therefore, the United States and allied democracies would retain design and production capacity proportionate to whatever degree other countries fail to develop capacity.[12] Countering China's subsidies could also prevent China from replacing globalized, market-disciplined supply chains—which contribute to strength, innovation, and therefore supply chain resilience in the global and U.S. semiconductor ecosystems[13]—with siloed, brittle, state-driven counterparts.

Over the last several decades, the United States has increasingly lost ground in fab capacity,[14] and now contains only 10 percent of global shares within its borders.[15] Especially precarious is America's advanced capacity in "foundries"—fabs that manufacture chips based on third-party chip designs. U.S.-based chipmaker Intel still competes in producing state-of-the-art chips, but is falling behind international leaders.[16] It operates under an "integrated device manufacturer" model to manufacture chips largely based on its own chip designs. Intel does not manufacture at scale chips customized for third parties, such as the U.S. government. GlobalFoundries is the top firm operating U.S.-based foundries. However, in 2018, GlobalFoundries announced it would stop advancing its manufacturing technology beyond its 12 nm node—now five years behind the state of the art and only becoming more antiquated with time.

These trends threaten the production of state-of-the-art U.S.-designed chips. Because there are no state-of-the-art domestic foundries, leading U.S. "fabless" firms—such as AMD and Nvidia—design chips but outsource fabrication to foreign foundries. If these fabless firms cannot access foreign foundries in a crisis, they will entirely lose the ability to produce the most advanced chips. The Department of Defense has a trusted suppliers program that accredits U.S. semiconductor firms with secure manufacturing processes to manufacture DoD-specific chips.[17] Relying solely on U.S.-based foundries, the DoD is now locked out of more advanced chip manufacturing technology—imperiling the advancement of critical defense technologies.[18]

Recent efforts seek to solve these supply chain security problems. With U.S. government support, leading Taiwan-based chipmaker TSMC has announced plans to open a small 5 nm U.S. foundry.[19] The U.S. government is also encouraging Intel to build a state-of-the-art foundry in the United States.[20] More efforts to bring advanced fab capacity to the United States, including through incentives and export controls, could ensure further supply chain security for the U.S. government and for U.S. chip designers.[21]

Apply Export Controls on Chokepoints

Multilateral or plurilateral export controls should target chokepoints in China’s supply chain to maintain its dependence on imports for advanced chips and improve U.S. and allied supply chain security. Export controls on these chokepoints should accomplish two goals: slowing China’s fab buildup and slowing the development of its chip design capabilities. If these policies succeed at maintaining China’s chip dependence, then the United States and its allies should control China’s chip access (a third goal). Table 1 summarizes export control options on chokepoints to achieve each goal. Table 1 includes the most important chokepoints for targeted export controls, which are this section’s focus, while Table 4 in Appendix B lists additional, less important chokepoints for an expanded approach. Table 4 summarizes the degree to which existing export controls currently exploit these chokepoints. Related CSET research analyzes these existing export controls in more detail.[22]

Table 1: Export control options

Goals		Slow China’s fab buildup		Slow improvement of China’s chip design capabilities		Control China’s chip access
Chokepoints and current leaders		Directly slow fab buildup	Slow photomask production	Directly slow improvement in chip design	Slow EDA develop-ment	
Materials	Photomasks (Japan, U.S., Taiwan, South Korea)	Control photomasks				
	Photoresists (Japan, U.S., South Korea)	Control photoresists				
Chip design	EDA software (U.S.)	Control EDA and fab collab.		Control EDA software		Control chips made abroad with EDA software
	Chip design IP (U.S., U.K., Israel)			Control chip design IP		Control chips made abroad or in China with chip design IP

Chip design, continued	Advanced fabs (U.S., Taiwan, South Korea)				Control process design kits	Control chips
Fab equipment	Chipmaking equipment: Photo-lithography	Control photo-lithography equipment				Control chips made abroad with photo-lithography equipment
	Chipmaking equipment: Non-photolithography (U.S., Japan, others)	Control select chipmaking equipment chokepoints				Control chips made abroad with chipmaking equipment
	Mask-making tools (U.S., Japan, Germany, Sweden)		Control mask-making tools			

Given the complex supply chain and multiple possible points of intervention summarized in Table 1, policymakers should implement these controls in a logical fashion that reflects not only the three goals in order, but also the best points of leverage for each goal. This decision logic is summarized in Figure 1. The following subsections—summarized below—walk through these options in detail.

First, to slow China's fab buildup (**goal 1**), policymakers should consider controls that deny Chinese fabs access to various inputs:

- chipmaking equipment[23]
    - either lithography tools only (**option 1A**),
    - certain non-lithography tools (**option 1B**),
    - or both (**option 1C**);
- materials (photoresists and photomasks) and equipment to make photomasks (**option 2**); and
- EDA software (**option 3**).

These controls are more likely to be effective than controls aimed at slowing development of China's chip design capabilities (**goal 2**).

If controls on fab equipment and materials are not politically possible or do not succeed, then to slow improvement in China's chip design capabilities (**goal 2**), policymakers should consider controls that

- deny Chinese chip designers access to
    - EDA (**option 4A**), and
    - design IP (**option 4B**); and
- deny China's EDA firms access to fabs' manufacturing process design kits (**option 5**).

If successful, export controls on chipmaking equipment, materials (and related equipment), EDA, or IP (**options 1–5**) will limit China's local design and/or fabrication capacity (**goals 1–2**) to less advanced levels of development, or "nodes."[24] A chip at a new node (e.g., 5 nm) contains approximately double the transistor density as a previous node (e.g., 7 nm) and is also more cost-effective. China has advanced as far as 7 nm in design capability and 14 nm in fab capacity. Table 2 lists implications of various potential control thresholds. A ≤45 nm threshold is the boldest available option, while ≤28 nm or ≤16 nm would be more sustainably effective. A ≤5 nm threshold would have a muted impact, so should remain a fallback position if China makes substantial progress in SME but fails to develop EUV tools.

Table 2: Implications of different export control node thresholds

Node threshold	**≤45 nm**	**≤28 nm**	**≤16 nm**	**≤5 nm**
SME used below this threshold	ArF immersion lithography predominant[25]	ArF immersion lithography required; other tools for new transistor materials[26]	Tools for advanced transistor structures[27]	EUV lithography required[28]
Cost-effectiveness of chips outside threshold[29]	25x more costly than state-of-the-art 5 nm	13x more costly than state-of-the-art 5 nm	5x more costly than state-of-the-art 5 nm	<2x more costly than state-of-the-art 5 nm
Projected 2021 Chinese SME market below threshold[30]	$9.6 billion	$7.5 billion	$1.1 billion	$0
China's SME indigenization effort within the threshold	Moderate: China is developing capabilities in this threshold, but will take years to build comprehensive capabilities		Low: China is not attempting comprehensive efforts indigenizing SME in this range in the near term	

Goals achieved with export controls applied within threshold	China has significant ≤45 nm fab capacity, but would fail to build more	China has a small amount of ≤28 nm fab capacity, but would fail to build more	China has minimal ≤16 nm fab capacity, would struggle to maintain it, and would fail to build more	China has no ≤5 nm fab capacity, and would fail to build any
Effectiveness of export controls	**Moderately effective in near term**: China's SMIC uses ArF immersion for 40 nm, but has substantial capacity already, so controls would have limited effect on China's ≤45 nm chip access	**Highly effective in at least the near term**: China must indigenize a variety of 28 nm tools, which it is attempting, but may struggle to do in the near-term	**Highly effective in medium or long term**: In the near term, China is unlikely to develop 16 nm SME, and revenue impacts to non-Chinese SME firms would be low	**Highly effective in long term**: China must develop EUV, which may take over a decade, but this threshold may have too limited an effect on China's capacity

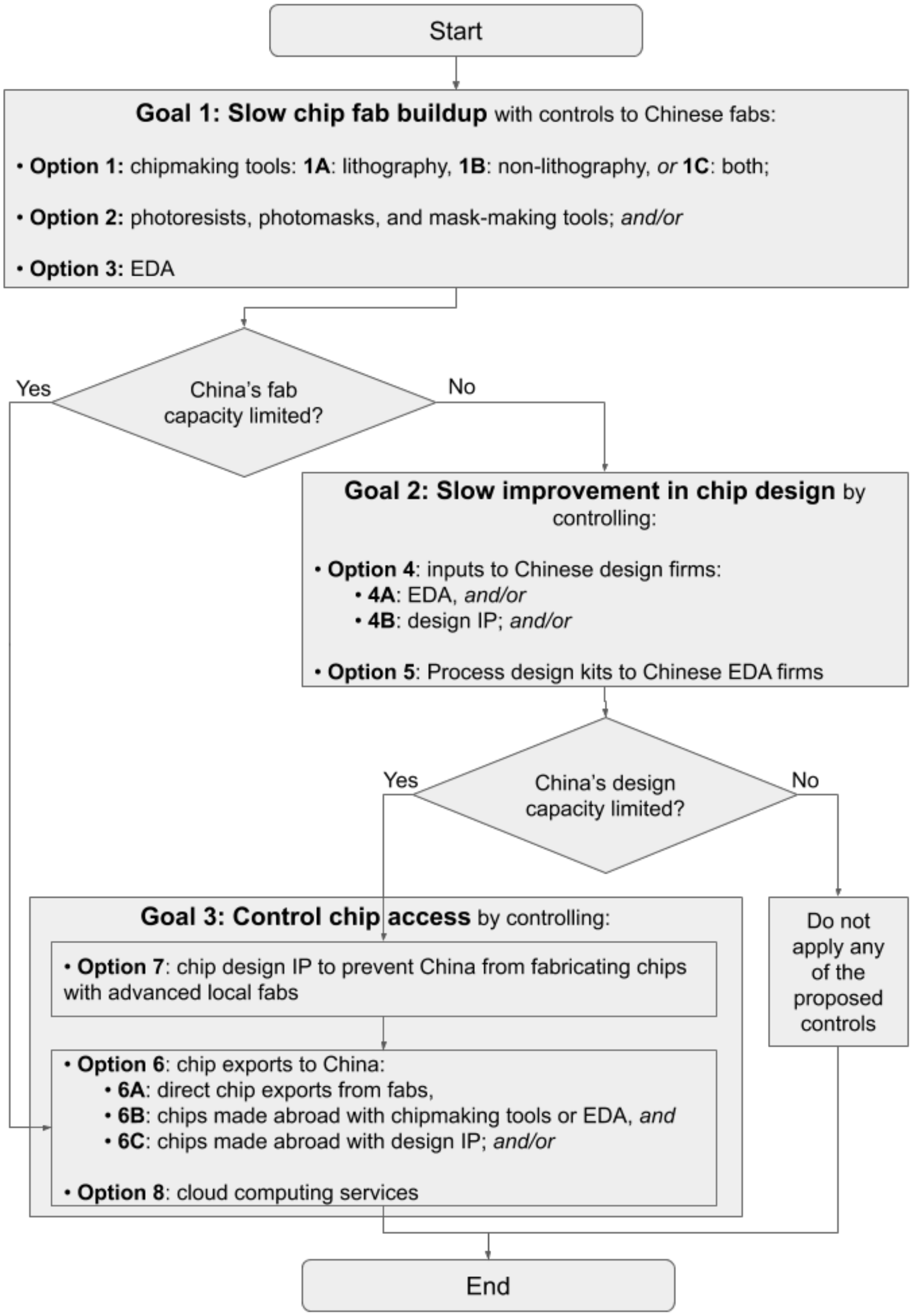
If slowing China's chip fab buildup succeeds (**goal 1**), then policymakers should apply targeted controls to prevent the Chinese government and other actors of concern from gaining access to advanced chips below the node threshold to use in ways that harm international security or human rights (**goal 3**). These controls could employ one or more of three tools:

- direct controls on chips (**option 6A**),
- controls on chips made abroad using chipmaking equipment or EDA software (**option 6B**), or
- controls on chips made abroad using design IP (**option 6C**).

These controls could additionally apply to large cloud computing services (**option 8**). However, chip exports should be permitted for civilian uses.

If slowing China's chip fab buildup does not succeed (**goal 1**), but slowing development of China's chip design capabilities does (**goal 2**), then controls on chips would require the chip controls above (**options 6A–C and 8**) plus controls on direct exports to China of chip design IP to prevent the country's fabs from manufacturing chips based on that IP.

Figure 1: Export control decision flow



Box 1: Considerations to apply export controls effectively

To be effective, controls should be enforced with a presumptive denial of export licenses—under congressional oversight—when the buyer is a Chinese fab. Under the case-by-case U.S. licensing policy currently governing most controlled SME and other semiconductor technologies, licensing officers typically approve licenses. This policy prevents export controls from having significant effect.[31] Congress could oversee decisions to ensure they follow the policy of presumption of denial.

Policymakers could craft controls to exempt (under appropriate conditions) fabs and chip design sites in China owned by firms headquartered in the United States and allied democracies. U.S., Taiwanese, and South Korean chipmakers have advanced fabs (Table 6 in Appendix D). If these fabs abide by U.S. and allied controls on chips, then the United States and its allies could continue to export fab equipment and materials to them. Similarly, Chinese operations of U.S. and allied chip designers could continue to receive chip design IP and EDA if they obey export control laws. However, the United States and its allies should restrict exports to newly planned non-Chinese fabs or chip design sites in China.[32]

Controls should be applied plurilaterally by all producing countries[33] and only when China cannot produce the controlled item,[34] or should not be applied. Analyses suggest that broad unilateral U.S. controls on China would prompt the decline of the U.S. semiconductor industry.[35] Many key firms get substantial revenue from China (Table 5 in Appendix C). Even a case-by-case licensing policy that typically results in approvals could cause nearly equivalent harm. Customers could face export licensing delays and fear denials, prompting them to buy equivalent technology from non-U.S. suppliers.[36] Achieving consensus on the multilateral controls suggested in this report under the Wassenaar Arrangement—an international export control treaty with 42 members including Russia—may prove slow and difficult. Therefore, semiconductor-producing members—particularly the United States, South Korea, Taiwan, Japan, the Netherlands, Germany, and the United Kingdom—should create a new plurilateral forum to align semiconductor-related export controls, licensing policies, and entity listings.[37] Members should then revise their national laws to implement aligned controls suggested in this report. They should also judiciously apply controls extraterritorially if firms headquartered in member countries move production to countries outside the plurilateral forum.[38]

Control technical data strictly but deemed exports more permissively. Controls should cover not just commodities (like SME and materials) but also technical data (i.e., the IP) associated with commodities.[39] Controls on technical data would reduce technology transfer and prevent non-Chinese firms from offering repair services for SME previously imported by

China. However, controls on “deemed exports” should be narrowly tailored with fast license processing to ensure foreign nationals can contribute to U.S. industry. Deemed exports require U.S. employers to apply for export licenses to release controlled technical data or source code to foreign nationals (those without a U.S. green card or U.S. citizenship).

Goal 1: Slow Chip Fab Buildup

The United States and its allies should slow China’s fab buildup (goal 1) to ensure China remains dependent on them for imports of advanced chips and to spur new fab construction in the United States and allied democracies to meet China’s chip demand. The following bullets summarize export control options to slow China’s chip fab buildup.

- **Option 1: Chipmaking tools.** The United States, the Netherlands, Japan, and others (as needed) should control chipmaking equipment—SME used for chip fabrication[40]—in any of three ways:
    - **Option 1A: Lithography only.**
        - The Netherlands should continue to control exports of extreme ultraviolet (EUV) scanners and the Netherlands and Japan should control argon fluoride (ArF) immersion scanners, necessary for mass production of advanced chips and China’s most important chokepoints. The United States and Germany should ensure that inputs to EUV scanners are controlled, including light sources, mirrors, and laser amplifiers.
        - Japan can also control advanced resist processing tools (also called tracks) used as part of the EUV and ArF immersion photolithography process.
        - To prevent China from producing advanced chips at low volumes, the United States, Japan, and Germany should continue to control electron-beam lithography; the United States, Austria, Germany, Japan, and Sweden can control nanoimprint lithography; and Sweden and Germany can control laser lithography.
    - **Option 1B: Other chipmaking tool chokepoints.** If the Netherlands does not join, the United States, Japan, and other partners (if needed) can control chipmaking equipment

chokepoints except lithography. The following are significant (but non-exhaustive) chokepoints:[41]

    - The United States, Japan, and the United Kingdom can control atomic layer etching tools.[42]
    - The United States, Japan, and Taiwan can expand controls on advanced ion implanters.
    - The United States, Japan, and depending on which tools are selected, other partners (the Netherlands, Germany, Israel, and/or South Korea) can control various types of metrology and inspection tools.
  - **Option 1C: All chipmaking tool chokepoints.** The United States, Netherlands, Japan, and other partners (if needed) can control all chipmaking equipment chokepoints listed above for options 1A and 1B.
- **Option 2: Materials and related equipment.**
  - The United States, Japan, South Korea, and Taiwan should control photomasks,[43] and to slow China's local development of photomasks, the United States, Japan, Germany, and Sweden should continue to control the mask-making equipment (electron-beam and laser lithography tools) needed to make them.
  - The United States, Japan, and South Korea can expand controls on photoresists.
- **Option 3: EDA to Chinese fabs**.
  - The United States should control exports of EDA software to Chinese fabs, preventing EDA firms from developing software supporting Chinese fabs' advanced nodes. However, other legal tools besides export controls may be necessary to prevent Chinese fabs from sharing IP with U.S. EDA firms.

The sections that follow develop each option in greater detail.

Option 1A: Control Lithography Only

Between options 1A–C, a lithography-only approach is simple and high-precision. Lithography is highly specific to particular nodes. Therefore, export controls can target specific node thresholds. Without access to lithography tools for a particular node, Chinese fabs will not purchase complementary chipmaking equipment used in the same manufacturing line. This approach would reduce the complexity of export licensing involving non-lithography chipmaking equipment.

The Netherlands and Japan should control both EUV and ArF immersion scanners. EUV scanners are necessary for mass producing 5 nm node chips, while EUV and ArF immersion scanners together are the only lithography tools capable of mass producing chips at ≤28 nm (with ArF immersion tools predominantly used for ≤45 nm).[44] In 2019, the Dutch government decided not to renew an export license for Dutch photolithography tool vendor ASML to ship EUV tools to China, limiting China's fab potential to the 7 nm node.[45] The United States, the Netherlands, and Japan should pursue additional export bans on ArF immersion tools to limit China's new fab construction below the selected export control threshold. Japan should further control resist processing tools used with EUV and ArF immersion scanners to complement controls on the scanners themselves. Additionally, the United States and Germany should ensure that exports to China of inputs to ASML's EUV scanners are controlled, such as light sources, mirrors, and laser amplifiers.[46] These controls make it more difficult for Chinese firms to produce EUV scanners.

To further constrain low-volume chip production—such as for military chips—the United States, Japan, Germany, and Sweden should continue to control electron-beam and laser lithography.[47] The United States, Japan, Germany, Sweden, and Austria should continue to control nanoimprint lithography, currently used in niche cases for chips. Future innovations could enable its use in high volume chip production.[48]

Although this approach is well-targeted and requires U.S. collaboration with only two countries, the Netherlands may choose not to apply strict controls, with license denials, to EUV and ArF immersion scanners.

Option 1B: Control Chipmaking Equipment Chokepoints Except Lithography

If the Netherlands does not participate in lithography controls,[49] the United States and Japan[50] could lead plurilateral controls on other chipmaking equipment chokepoints. Japan's inclination to collaborate with the United States on export controls likely makes this easier to achieve than a three-way partnership.

Good candidates for control are atomic layer etching tools (by the United States, Japan, and the United Kingdom), advanced ion implanters (by the

United States, Japan, and Taiwan), and metrology and inspection tools (by the United States, Japan, and depending on which tools are selected, the Netherlands, Germany, Israel, South Korea, and/or France). For certain advanced versions of these tools, cooperation by only the United States and Japan may be sufficient. For other potential chipmaking equipment chokepoints, see Table 4 in Appendix B.

This approach may require more complex controls, a more advanced node threshold, and may be effective for a shorter time compared to photolithography controls, as China's most promising development prospects are in non-lithography SME. Some non-lithography chipmaking equipment is less specific to nodes, making it hard to apply export controls to specific nodes. If the export threshold is >16 nm, then chipmaking equipment export licenses could be denied if the destination is a ≤16 nm fab, and granted if it is a >16 nm fab or used outside of fabs. Risks of diversion from >16 nm fabs to ≤16 nm fabs would be low, as there is no precedent for diverting chipmaking equipment in China;[51] these are large, precision pieces of equipment that fill rooms and are easy to damage. As a result, SME firms typically help install chipmaking equipment in fabs. Nevertheless, to guard against diversion, export licenses could be denied to any firm that owns a ≤16 nm fab until that firm divests it, or exporting countries could require inspection.

Option 1C: Control All Chipmaking Equipment Chokepoints

If all necessary countries participate in export controls, they could be expanded to all chipmaking equipment chokepoints (i.e. those identified for options 1A–B). This approach would be more complex than a sole focus on lithography. Yet by putting more "skin in the game" by controlling its own technology, the United States would invite cooperation from the Netherlands and Japan in strictly controlling EUV and ArF immersion photolithography tools, which the United States does not produce.[52] Additionally, this approach would provide insurance. Facing export controls only on lithography, China could invest billions of dollars of state subsidies per year in lithography. China's Shanghai Micro Electronics Equipment (SMEE) has purportedly developed a 90 nm ArF tool and plans to introduce a 28 nm ArF immersion tool in the near future.[53] Still, building a commercial tool with low cost, low manufacturing error rates, and high throughput can take years after initial prototyping. [54] Therefore, no fabs are using SMEE's tools for mass chip production. Even when developed, SMEE's ArF immersion tool's throughput is expected to be less than a third of leading commercial tools' throughput.

China's prospects to catch up to ASML are dim in the foreseeable future. CSET estimates that China will not develop commercial EUV tools for at least a decade, and may never succeed in doing so.[55] But a surprise is possible. In this scenario, as China climbs the feature size ladder of photolithography capabilities, it could import complementary equipment to build new fabs. On the other hand, the prospect of simultaneously indigenizing all of its chipmaking equipment chokepoints in parallel is daunting. China may balk at the expense and difficulty, instead resorting to chip imports.

Option 2: Control Materials and Related Equipment

On top of the above approaches to chipmaking equipment controls, the United States and its allies could expand controls on advanced photomasks, advanced photoresists, and mask-making equipment (electron-beam and laser lithography tools).[56] By combining controls on materials with controls on equipment needed to make them, China would face difficulty indigenizing these technologies. Photomasks and photoresists are node-specific, so under export controls with node thresholds, identifying which ones to control would be straightforward. A photomask is specific to one chip design that itself is specific to a node, while photoresists are specific to photolithography processes, such as EUV and ArF immersion, themselves specific to ranges of nodes.[57]

Box 2: Effects of Export Controls on Equipment and Materials

China's advanced fab capacity below the cutoff node threshold would freeze in place or even shrink.[58] More speculatively, given chipmaking equipment controls, China could fail to repair existing stock of imported chipmaking equipment in fabs below the node threshold for export controls.[59] Although this imported chipmaking equipment could take years to fall into disrepair, China's may fail to maintain its 14 nm or even 28 nm[60] domestic fab capacity.[61] Controls on photomasks and mask-making lithography tools could have a similar effect. Controls on photoresists—consumable inputs requiring continual replenishment, like ink cartridges for a printer—could cause China's existing advanced fabs to more quickly lose capacity.[62]

New fabs would be constructed in the United States and allied democracies instead of China, with little long-term impact to SME and materials firms. Currently, the global semiconductor market can support just a handful of state-of-the-art fabs.[63] Today, only Taiwan-based TSMC, South Korean-based Samsung, and U.S.-based Intel operate fabs at the state of the art. Three technology generations behind the state of the art, China's top chipmaker Semiconductor Manufacturing International Corporation operates with low production volume at a technological level achieved by leading chipmakers in 2015. (SMIC is already subject to unilateral and permissive U.S. export controls.)[64] While China's semiconductor subsidies have been ineffective for decades,[65] the slowing of Moore's Law—given increasing costs and technical challenges in shrinking transistors—could help China catch up. In this scenario, SME and material export restrictions would forestall China's state-of-the-art capacity and help ensure the United States, South Korea, and Taiwan do not suffer an equivalent loss of capacity. Fabs are outfitted with fixed production capacity, served by a fixed proportion of SME and consumable materials. In the long term, to serve global chip demand, U.S. and allied democracies would instead build that same production capacity and buy the same proportion of SME and materials China would have in the absence of export controls and subsidies.[66] Therefore, after a near-term revenue decline due to supply chain reconfiguration and loss of Chinese subsidies—which encourage extra purchases—SME and materials firms would experience only minimal long-term revenue losses.[67] Additionally, U.S. and allied fabs would be less likely to block imports than China, creating more reliable partners for SME and materials firms. (While recognizing these effects, the United States and its allies should limit export controls to mitigating risks to human rights and security, and avoid using them for purely economic objectives.[68])

China's attempts to build its SME and materials industries, and semiconductor industry more broadly, would be set back. First, export controls would stem the transfer of technical know-how to China by preventing: firms in the U.S. and allied countries from building R&D sites in China; Chinese access to the SME and materials for reverse-engineering; and U.S. and allied firm support staff from assisting with the operation of China's imported SME and materials. Second, absent new advanced fabs and potentially even maintenance of existing advanced fabs, China's semiconductor industry would lose absorptive capacity for further innovation.[69] Fewer engineers would accumulate relevant skills and China could lose local customers for domestically produced SME. Third, if its advanced fabs shut down, China may balk at the costs of restarting them if it regains access to SME and materials;[70] even temporary controls could slow the long-term trajectory of China's semiconductor industry.[71]

Option 3: Control EDA Software to China's Fabs

EDA software presents a unique opportunity: the United States enjoys 96 percent market share and solely produces EDA tools capable of fully designing advanced chips.[72] The United States should prevent EDA firms from receiving process design kits from Chinese fabs to develop EDA software supporting Chinese fabs' advanced nodes. A PDK is unique to each chipmaker and node. EDA tools use the PDK to design a chip based on the manufacturing process modeled by the PDK. Without software to produce chip designs for manufacture at advanced Chinese fabs, these fabs are unusable. While export controls may play a role, other legal tools could be necessary to stop U.S. EDA firms from collaborating with Chinese fabs—particularly in cases where only the fab passes IP to the EDA firm, but the EDA firm does not share any IP with the fab.

Goal 2: Slow Improvement of Chip Design Capabilities

If slowing China's chip fab buildup (goal 1) does not succeed, then the United States and its allies should instead consider slowing improvement of China's chip design capabilities. Maintaining China's dependence on foreign design IP to locally manufacture advanced chips (goal 2) would create the possibility of targeted export controls on advanced chips and the foreign design IP for China to make them locally.

The following bullets summarize export control options to slow improvements in China's chip design capabilities.

- **Option 4: Inputs to Chinese chip designers.** At the risk of impacting revenues of EDA firms and chip designers, policymakers should only expand export controls in these areas if plurilateral efforts to control SME and materials fail. Even then, they should carefully weigh upsides and downsides before applying controls for advanced and specialized EDA capabilities and chip design IP.
    - **Option 4A: EDA.** The United States could control EDA software used by Chinese chip designers.
    - **Option 4B: Chip design IP.** The United States could control x86 CPU, GPU, and FPGA design IP licensed by Chinese chip designers. The United States and United Kingdom could also control core IP licensed by Chinese chip designers.
- **Option 5: Manufacturing process design kits**. The United States could control advanced fabs' process design kits to slow the development of China's EDA sector. These controls are less risky, posing only minimal revenue risks from leading chipmakers' potential lost partnerships with China's fledgling EDA sector.

The sections that follow develop each option in greater detail.

Options 4A and 4B: Control EDA Software and Chip Design IP to China’s Chip Designers

Export controls on EDA software and advanced chip design IP could limit China’s advanced chip design activities. They would therefore also slow China’s efforts to displace the United States’ locked-in chip architecture advantage[73] through technology transfer[74] and development of alternative chip architecture ecosystems.[75] To the extent Chinese chip designers cannot design chips specialized for applications demanded by the domestic market, U.S. and allied chip designers can gain business lost by China. (Unlike the EDA controls described under option 3, these controls would stop collaborations with Chinese chip designers rather than Chinese fabs.) Currently, the United States dominates EDA and the design of key chips, including x86 CPUs, GPUs, and FPGAs. And the United States and the United Kingdom are key providers of core IP licensed to Chinese chip designers to design a variety of chips.

However, export controls could harm U.S. EDA firms[76] and U.S. and U.K. chip design firms even while reducing China’s local design capacity.[77] EDA piracy could also render EDA controls less effective than desired.[78] Therefore, such controls should be a backup option to be applied narrowly. An appropriate balance could be to limit access to EDA software and design IP that supports state-of-the-art nodes,[79] with features or IP specific to designing complex, specialized, or security-relevant chips such as leading-edge AI training ASICs,[80] or to end-users designing such chips. Even then, controls may be ineffective for any EDA tools already sold as on-premise software, as they can be pirated.

Option 5: Control Process Design Kits

The United States, Taiwan, and South Korea could control PDKs for its most advanced nodes, particularly ≤10 nm and below. Doing so would prevent Chinese EDA firms from supporting chip designers outsourcing manufacturing to state-of-the-art fabs—Intel, TSMC, and Samsung—in these countries and protect the competitiveness of U.S. EDA software vendors.[81] These controls are less risky than those on EDA software and design IP, posing minimal revenue risks to any U.S. and allied semiconductor firms.

Goal 3: Control Chip Access

If the above export controls slow China's chip fab buildup (goal 1) or design capabilities (goal 2), China will remain reliant on the United States and its allies—especially Taiwan and South Korea—for imports for state-of-the-art chips and advanced specialized chips, such as AI chips. The United States and its allies should then apply targeted export controls to stop the Chinese government and other actors of concern from accessing advanced chips in ways that harm international security and human rights (goal 3). Critically, chip export controls should be narrowly tailored to capture security-relevant end-uses and end-users, with exports broadly permitted for peaceful, commercial uses. The following bullets summarize export control options to restrict China's access to advanced chips.

- **Option 6: Control chips**. If China lacks advanced fab capacity, the United States and its allies can pursue any of three approaches to controlling chips, or a combination.
    - **Option 6A: Directly control chips**. The United States, Taiwan, and South Korea—whose firms dominate the world's advanced fab capacity—could control advanced chips.
    - **Option 6B**: **Control chips made abroad with SME or EDA**. The United States and Japan (and optionally, the Netherlands) could use the U.S. foreign-produced direct product rule (and foreign equivalents) to prevent any advanced fabs around the world from exporting chips made with SME to Chinese customers. And the United States could use the foreign-produced direct product rule to prevent any advanced fabs from exporting advanced chips designed with EDA software to Chinese customers.
    - **Option 6C: Control chips made abroad with design IP**. The United States and the United Kingdom could apply the U.S. de minimis rule (and U.K. equivalent) to prevent any advanced fabs from exporting chips made with certain advanced chip design IP.
- **Option 7: Control chips made in China with design IP**. If China has advanced fabs but lacks advanced chip design capabilities, the United States and its allies would need to apply at least one of the three above approaches to prevent access to foreign-manufactured

chips (options 6A–C). However, these approaches would need to be coupled with controls on direct exports to China of chip design IP to prevent Chinese fabs from manufacturing chips based on those designs.

- **Option 8: Control cloud compute services**. The United States should partner with countries providing large amounts of cloud computing services to vet and control large cloud computing purchases. Otherwise, purchasing cloud computing would provide a "backdoor" path for China to access high-end computing on chips otherwise inaccessible.

The sections that follow develop each option in greater detail.

Box 3: Permit Chip Exports for Civilian Uses

Whatever approaches are used, chip export controls should be narrowly crafted toward security-relevant end-uses and end-users, with exports broadly permitted for peaceful, commercial uses. The United States and its allies should deny chip exports to the Chinese state, supercomputing entities, human-rights violators, and those collaborating with the Chinese military.[82] This policy would prevent the proliferation of dangerous technologies and preempt arms races, as well as advance global security, democratic values, and human rights, including for Chinese citizens. Meanwhile, allowing exports for peaceful commercial uses would avoid unnecessarily harming China's broader economy. In contrast to export controls on certain supply chain inputs that produce chips, such as SME, broad export controls on chips to China could sharply impact revenues in both the near term and long term. Given the large revenue exposure of U.S. chipmakers to the Chinese market, broad chip controls could severely and irreparably harm the U.S. semiconductor industry. Moreover, private Chinese spending on U.S. and allied chips—currently in the range of hundreds of billions of dollars a year—dwarfs China's $15 billion a year in state subsidies to its own industry. Thus, continued exports of chips for civilian uses would help sustain the preeminence of the U.S. and allied semiconductor industries.

Option 6A: Control Exports of Chips from Fabs

The first approach is for countries with fabs to control manufactured chips, particularly the United States, Taiwan, and South Korea, where the world's only fabs with ≤10 nm capacity are headquartered. Table 6 in Appendix D lists the most advanced ≤45 nm current or planned logic foundries, logic IDMs, and memory IDMs by firm headquarters within each country. The

United States can craft export controls extraterritorially to capture U.S.-based firms with fabs abroad via the de minimis rule, the foreign-produced direct product rule, or based on the nationality of these firms; other participating countries can do the same.[83]

Option 6B: Control Chips Made Abroad from U.S. and Allied Equipment or Software

If multilateralism is difficult to achieve under the first approach, countries controlling supply chain chokepoints—the United States and Japan (and optionally, the Netherlands)—could use the U.S. foreign-produced direct product rule and its foreign analogues to control worldwide advanced chip access.[84] Under the rule, export controls apply to a chip made abroad if U.S.-origin content controlled for national security purposes is used to produce it. As dominant producers of many non-lithography chipmaking tools and EDA tools, the United States could impose advanced chip controls on advanced fabs worldwide.[85] In 2020, the United States unilaterally passed an expanded version of this rule specific to Huawei. It requires export licenses for chips manufactured by any fabs in the world using U.S. equipment, software, or technical data whose exports to China are otherwise not controlled.[86] This unilateral approach proved effective—evidenced by Taiwanese chipmaker TSMC's compliance[87]—as no advanced fab will be able to operate without U.S. SME for the foreseeable future. Still, multilateral approaches are best, ideally with Japan's cooperation.[88]

The difficulty of enforcing extraterritorial controls and the imposition on U.S. allies makes this approach less desirable than harmonized plurilateral controls by countries with advanced chip fabs. Therefore, this tool should be used narrowly and judiciously in cases of major risks to national and international security when such cooperation fails. This lever could also serve as a bargaining tool to achieve plurilateral cooperation on direct controls on chips (Option 6A).

Option 6C: Control Chips Made Abroad from U.S. and Allied Chip Design IP

A third approach is for countries with advanced chip design firms—particularly the United States and the United Kingdom—to control chip design IP using an amended version of the U.S. de minimis rule and its foreign analogues. Currently, under the de minimis rule, U.S. export controls apply to a chip if an item includes a threshold percentage of U.S.-origin content controlled in the receiving foreign country.[89] If the receiving foreign country is

China, the de minimis threshold is zero percent for controlled chips,[90] with the exception of 25 percent for controlled memory chips. For uncontrolled chips, the threshold is also 25 percent. Currently, the de minimis rule does not count technical data (e.g. IP) toward the threshold when it is incorporated into a physical commodity, such as a chip. This loophole could be closed for specified chip exports to China.[91]

Option 7: Control Exports of Chip Design IP

If China's bottleneck is advanced fab capabilities, the United States and its allies should restrict China's chip access by applying one or more of the above export controls (options 6A–C). Yet if China contains advanced fabs but lacks advanced chip design capabilities, a different approach is needed. The United States and its allies would need to apply at least one of the above export controls to prevent access to foreign-manufactured advanced chips. These controls must then be coupled with controls on direct exports to China of chip design IP to prevent its fabs from manufacturing chips with that IP. Alternatively, foreign chip designers could be required not to sell those chips manufactured in China to prohibited end-users in China.

Option 8: Control Cloud Compute Access

While currently not covered export controls, the United States should identify countries providing large amounts of cloud computing services. It can then collaborate with them to extend export controls to large cloud computing purchases to use controlled chips. Determined actors can gain access to controlled chips by purchasing cloud computing services. For example, a Chinese entity could set up a shell company in the United States and anonymously purchase cloud computing services from U.S. vendors. That entity can also access cloud computing services anonymously through proxy servers. Because these purchases do not require chip exports, they are not captured by export controls. Policymakers should consider closing this loophole for large purchases. For example, cloud computing vendors could be required to vet the identity of customers and their planned end-uses if these customers make purchases above a large threshold. In cases where an export license would have been needed for the same chips exported to a customer, the policy could require such a license. If the cloud computing vendor doubts the real identity of the customer, it could be required to take reasonable efforts to discover the identity. More research is needed to identify the ideal legal tool to close this loophole.

Box 4: An AI Governance Proposal: Monitoring and Controlling AI Chips

Using policy tools 6–8, the United States and its allies should monitor and, if necessary, apply narrow, targeted controls on AI chips[92] necessary to cost-effectively train cutting-edge AI systems. Such chips include leading-edge[93] server-grade[94] GPUs, FPGAs, and AI training ASICs.[95] First, they should impose reporting requirements—to identify purchasers and the types and numbers of chip sold—for exports, re-exports, and in-country transfers to or within countries of concern.[96] Then, the United States and its allies can apply controls on actors found to be developing or deploying AI unsafely or unethically in ways that could prompt a race to the bottom compromising safety in advanced systems, or for military applications.[97]

Different policy tools are available. First, the United States can implement this regime unilaterally under the foreign-produced direct product rule (option 6B). This option is the simplest and most powerful. Second, the United States, Taiwan, and South Korea—which house the vast majority of logic fabs capable of manufacturing leading-edge AI chips (see Table 6 in Appendix D)—can monitor and control chip exports from fabs (option 6A).[98] Third, the United States can monitor and control direct exports (option 7) and re-exports under the de minimis rule (option 6C) of AI chip designs. U.S. firms design all server-grade GPUs and FPGAs and most AI training ASICs, so the United States can achieve much of the effect unilaterally. However, a few firms in the United Kingdom and Israel also design commercial AI training ASICs and may need to participate.[99] And chip design controls under the de minimis rule would not prevent Chinese firms from outsourcing their own AI chip designs for fabrication at foreign foundries, such as TSMC.[100] Effective chip design controls would require China's fabless design sector to be incapable of designing advanced AI chips, either due to its own difficulties or export controls on EDA software and design IP. Therefore, chip design controls are best coupled with other approaches. Finally, the United States and its allies should implement a vetting regime for large purchases of AI computing power from cloud computing services (option 8).

Explore Related Policy Options

Policymakers should explore five related policies. These policies would stand on their own, but would also increase the effectiveness of export controls if implemented alongside them.

Fund Public-Private Partnerships

The United States should pursue additional public funding for R&D spending in partnership with industry and provide financial incentives for new U.S.-based fab construction. Currently, private funding eclipses public funding in semiconductor R&D. U.S. and allied semiconductor firms thrive due to the market discipline of the private sector—and their footprints should predominantly remain there. But more public funding is desirable on the margin due to rising costs of innovations,[101] revenue impacts of export controls described in this report, and comparatively poor U.S. incentives for fab construction compared to those of other countries.

R&D funding. A U.S. agency (such as the Defense Advanced Research Projects Agency) could partner on R&D with firms in the participating countries impacted by export controls. Each firm could receive R&D funding equal to projected gross margin losses, as this funding would arguably make firms indifferent to export controls (Appendix E explains why). Optionally, the intellectual property developed therein could then be licensed to all program participants.[102] Funding should focus on pre-competitive R&D, which benefits all firms in the relevant market[103] and generates large social returns,[104] without distorting competition. An alternative funding tool could be a refundable tax credit for R&D and production of controlled items, including SME.[105]

Funding amounts equal to gross margin losses would compensate firms impacted by export controls and convince U.S. allies to collaborate.[106] Table 7 shows sample calculations of gross margin losses for SME firms due to controls at various node thresholds.[107] If export controls are applied in a targeted, plurilateral manner as suggested in this report, then funding need only be a stopgap measure: firms would suffer near-term revenue losses, but minimal long-term impacts. Leading U.S. SME firms Applied Materials and Lam Research keep around 90 percent of their assets in North America.[108] However, if export controls are inappropriately applied, revenue losses—with long-term shortfalls unfilled by public funding—could increase semiconductor firms' incentives to transfer operations to countries without controls, as in the case of U.S. export controls on satellites.[109] The open-source chip design consortium RISC-V is moving its headquarters outside of the United States, anticipating U.S. export controls.[110] Some U.S. SME firms have already begun moving supply chains abroad in response to unilateral U.S. controls.

Additional R&D funding beyond the amounts needed to recoup export control losses would further boost semiconductor innovation. This funding should focus on advancements in critical chokepoints where the United and its allies already have substantial leads—SME, advanced materials, new chip design architectures, EDA, advanced fabrication, and advanced packaging—

to drive the semiconductor ecosystem in a direction sustaining existing U.S. and allied advantages.

Any funding should be harmonized with other new R&D funding efforts. In 2019, the U.S. semiconductor industry spent $39.8 billion on R&D,[111] while the U.S. government spent only $1.7 billion on semiconductor-specific R&D and $4.3 billion on semiconductor-related R&D.[112] However, in 2020, the Semiconductor Industry Association called for an additional $3.4 billion a year in semiconductor-specific R&D and $4.3 billion a year in semiconductor-related R&D by 2024,[113] plus tax incentives and other spending.[114] In 2020, Congress introduced the CHIPS for America Act, which contains at least $12 billion of R&D funding, and the American Foundries Act, with at least $5 billion of R&D funding.[115] The National Defense Authorization Act (NDAA) of 2021 incorporated provisions from these bills.[116] These efforts are a step in the right direction.

Financial incentives for leading-edge fab construction. The U.S. government should provide financial incentives for chipmakers to build state-of-the-art fabs, especially logic foundries, in the United States. This effort would reshore fab capacity to the United States.

The U.S. semiconductor industry has retained a leading market share and technological advantage across nearly all high-value segments of the supply chain, with a major exception of leading-edge chip fabrication. U.S. global fab capacity share today is 10 percent, having lost two-thirds of global share since 1990.[117] The United States also lacks any pure-play logic foundries more advanced than 12 nm. (A foundry makes chips for third-party customers, unlike Intel, whose leading-edge logic fabs make chips based on Intel's own chip designs.) The Department of Defense and top U.S. fabless firms now lack domestic foundry capacity to locally manufacture state-of-the-art chips. As a result, the U.S. government has already lobbied leading chipmakers Intel, TSMC, and Samsung to build leading-edge foundries in the United States, with Intel a candidate to build a foundry serving commercial and government customers.[118] In response, TSMC has announced plans to build a 5 nm foundry in Arizona.[119]

Incentives could include refundable tax credits and grants for fab construction costs and SME purchases. An industry analysis suggests that cost of ownership of U.S. fabs is greater than for fabs in Taiwan, South Korea, Singapore, and China. Incentives could fill this gap and stop or even reverse the decline in U.S. global fab capacity share.[120] The NDAA for Fiscal Year 2021 (taking provisions from the CHIPS for America Act and American Foundries Act) authorized grants for U.S. fab construction—and should be fully funded in appropriations legislation.

Reduce Unnecessary Trade Barriers

The United States should reduce industry-harming trade barriers, including economically motivated import tariffs and overbroad or unilateral export controls. These changes would help preserve U.S. industry competitiveness and reduce chances of retaliation by China.

The introduction of tariffs in July 2018 amid U.S.-China trade tensions coincided with a slowing of yearly growth of top U.S. semiconductor firms from 10 percent to 1 percent by late 2018.[121] A notable example of an unnecessary trade barrier is the 25 percent tariff applied to chips fabricated in the United States, but assembled, tested, and packaged (ATP) in China and exported back to the United States.[122] These tariffs harm the globalized supply chains for U.S. chipmakers like Intel, even though low-value-added ATP activities in China pose little risk of technology transfer.[123] Meanwhile, Chinese chipmakers export few chips to the United States, so they are less impacted by these tariffs.

Additionally, after the U.S. unilateral entity listing of Huawei in May 2019, top U.S. semiconductor firms saw median revenue declines of 4 to 9 percent due to loss of chip sales,[124] and Huawei began substituting with non-U.S. suppliers. In 2020, the U.S. Commerce Department closed this loophole by preventing Huawei from obtaining chips manufactured by any non-U.S. fabs, such as TSMC, using U.S. equipment.[125] Although these expanded controls reduce harms to U.S. industry, policymakers should study how much U.S. national security benefits from export controls if Huawei equipment is already barred from critical U.S. systems.[126]

Moreover, unnecessary U.S. trade barriers increase risks of Chinese retaliation, as discussed in a later section in Chinese responses to export controls. The United States and its allies can mitigate these risks by focusing export controls and other trade barriers on security-relevant technologies while reducing trade barriers motivated by economic competition—and instead promote positive-sum, shared economic prosperity for both countries.[127]

Challenge China's State Subsidies

The United States and its allies should further study China's market-distorting semiconductor state subsidies and their legality under the World Trade Organization, and launch trade negotiations or WTO challenges for China to reduce them. One study of 21 major semiconductor firms found that state subsidies to Chinese firms range from 20 to 40 percent of each firm's revenues, compared to less than 5 percent for all non-Chinese firms in the sample.[128] The full nature and scope of China's subsidies remain opaque and require further study. However, what's certain is China's industrial policy risks displacing leading U.S. and allied chipmakers and their robust, market-disciplined supply chains in favor of brittle, state-driven counterparts led by an authoritarian government. Export controls proposed in this report are, in part, aimed at undercutting this industrial policy, which poses risks to U.S. and international security. However, the United States should offer to drop more stringent versions of export controls in exchange for China ending its subsidies. For example, export controls could focus on a small set of core technologies like photolithography with cutoffs at leading-edge nodes (≤16 nm), rather than on a broader set of technologies with cutoffs at less advanced nodes. If China refuses, the United States and its allies should pursue strict export controls combined with WTO challenges on China's subsidies.

Develop and Retain Access to Top Talent

Maintaining the U.S. semiconductor industry's competitiveness and drawing supply chains to the United States requires sufficient access to top domestic and foreign talent.[129] The U.S. semiconductor industry competes for and relies upon high-end talent[130]—especially foreign-born.[131] Without access to sufficient talent in the United States, semiconductor firms would increasingly look outside the United States when opening new R&D sites or fabs. Other CSET research explores policy options to retain access to top talent: offering U.S. investment in research and education, sustaining the Optional Practical Training (OPT) program, eliminating country-based caps on green cards, and increasing the number of available employment-based visas.[132] However, given this report's focus on export controls, this section primarily suggests a narrow, targeted application of deemed export controls to balance the aims of foreign talent retention and technology transfer mitigation. Visa vetting processes already identify many foreign nationals at risk for espionage—making deemed exports at least somewhat redundant. Additionally, harsh deemed export controls would be inconsistent with the cosmopolitan values of the U.S. technology sector.

Deemed export controls should be as narrowly tailored as possible to reduce IP theft without deterring foreign nationals from working in U.S. industry. (A U.S. employer must apply for a deemed export license for a foreign national who lacks a U.S. green card or U.S. citizenship and who would access controlled technical data or source code in the United States during their employment.) In a notable recent case, former employees of ASML transferred IP to a Chinese lithography firm XTAL.[133] However, strict controls could prevent current or future immigrants not currently working in the semiconductor industry from joining it until they obtain green cards—starving the U.S. semiconductor industry of top talent. High-skilled immigrants overwhelmingly plan to (and do) stay in the United States if given the opportunity to obtain U.S. green cards.[134] Even well-targeted deemed export controls can harm U.S. industry if the Commerce Department lacks resources to process licenses quickly. In 2019, licensing delays reached nearly seven weeks on average for Chinese nationals with some delays reaching eight months.[135] Such delays can become *de facto* denials and should be eliminated.

Controls should therefore permit exemptions where possible. For example, if policymakers expand controls to new semiconductor technologies, they should exempt from related deemed export controls experienced foreign nationals employed at U.S. semiconductor firms, as they may leave for foreign firms when they would otherwise stay. In these cases, controls on technical data and source code associated with semiconductor technologies should be limited to the actual export of that information—with a license exemption for deemed exports. An upper boundary for the number of U.S.-based Chinese-national high-skill technical semiconductor and related industry workers is approximately 6,000,[136] compared to 241,134 U.S. semiconductor industry workers in the United States.[137] If policymakers broadly and strictly apply deemed exports—especially with license denials—to existing employees, firms would be forced to lay off Chinese nationals, accelerating their return to China. Another option is to grant general licenses to U.S. employers that institute sufficient security measures on their own.

Screen Investments to Reduce Technology Transfer

The United States and its allies should remain vigilant about attempts by the Chinese government and firms, as well as other competitors, to acquire semiconductor technology through IP licensing, investment, joint ventures, and mergers and acquisitions. These are key vectors for the acquisition of know-how, which is of central importance in the semiconductor industry.[138] Technology transfer is a collective action problem for the U.S. and allied semiconductor industries. While an individual U.S. firm can benefit from transferring technology, many firms doing the same would diffuse the know-how underpinning U.S. semiconductor preeminence to foreign competitors at the long-term expense of the U.S. semiconductor industry. The U.S. government is well-positioned to control technology transfer for the industry as a whole. Export controls on technical data and deemed exports play a role, as discussed earlier. However, actions by the Committee on Foreign Investment in the United States are also critical. CFIUS is an interagency committee that reviews transactions by foreign entities to determine whether they raise national security concerns. These transactions include, for example, investments in or mergers with U.S. firms. The U.S. president then blocks transactions on recommendations from CFIUS, and has taken many such actions in the recent past.[139] CFIUS should continue to comprehensively identify and vet similar transactions, including for current semiconductor chokepoints but also early-stage R&D that could form the basis of future strategic advantages. Partnerships enabling R&D centers in China that focus on special, lower-end products customized for the Chinese market are acceptable, so long as they cannot result in full IP transfer.[140]

China's Potential Responses to Export Controls

While the United States and allied democracies are well positioned to control China's access to chips and key inputs to produce them, policymakers must also consider China's potential responses: "in-kind" export controls on raw materials, increased technology indigenization efforts on controlled technologies, and restrictions and penalties on non-Chinese firms. The United States and its allies should mitigate these risks by narrowly targeting controls—especially on finished chips—to address harms to human rights or international security, and avoiding controls motivated purely by economic competition.

China could apply export controls on raw materials, especially rare earths and gallium, for which China dominates production.[141] See Appendix A for more details on U.S. import reliance on China for raw materials. More research is needed to better understand U.S. import reliance on China for other items, such as medical supplies.[142] China has not substantially restricted exports in response to tightening U.S. semiconductor controls since 2019 and broader U.S.-China trade tensions.[143]

China could further restrict exports of rare earths, which it already subjects to export quotas. According to Chinese state media, China could use its new export control laws on rare earths to retaliate against chip export controls by the United States.[144] Rare earths are used as chip materials and in chip fabrication steps including chemical mechanical planarization. The United States relies on imports, with 80 percent from China. After China briefly curbed rare earth exports in 2010, its global market share in primary production dropped from 97 percent to 71 percent by 2018.[145] The United States is now drawing from its rare earth deposits: the Mountain Pass mine in California, which once provided most of the world's rare earths, reopened in 2018 and now accounts for 12 percent of world primary production.[146] Still, China processes virtually all of the world's mined rare earths, including those mined in the United States.[147] U.S. refineries capable of processing at scale are in development, but may not open until 2022 or later.[148] The U.S. government can reduce this timeline with concerted policy efforts.[149]

China could control gallium to disrupt supply chains for chips made from gallium arsenide or gallium nitride wafers. However, this risk is only moderate for a few reasons. First, silicon wafers, not gallium arsenide or gallium nitride wafers, are used in the production of the vast majority of chips. Gallium arsenide or gallium nitride-based chips can better withstand certain environments, so are suitable for defense and space applications. Second, the United States relies on imports of Chinese gallium for only half its needs.[150] Third, non-Chinese gallium producers likely restrict output due to surpluses—which they may no longer do if China applies export controls.[151] In fact, gallium's global supply potential outstrips current production several times over.[152] Accordingly, the United States and its allies could find alternative suppliers after a near-term increase in costs. Fourth, in 2018, the United States applied 10 percent tariffs on Chinese gallium imports and in 2019 increased them to 25 percent.[153] U.S. and allied firms may move away from Chinese producers before China applies export controls.

China could accelerate technology indigenization. To indigenize technologies controlled by the United States and its allies, China could increase state subsidies (currently already substantial), talent recruitment efforts (especially from leading global firms), and technology transfer (such as by more aggressive hacking operations). A more drastic, unlikely action would be to nationalize non-Chinese semiconductor operations in China (see Table 6 for examples) to access their know-how—though most semiconductor firms do not make their most advanced products or perform their most advanced R&D in China. To favor domestic industry, China could reverse the strengthening of IP protections for non-Chinese firms in recent years.[154]

Forthcoming CSET research analyzes China's efforts to build its SME industry and concludes China will likely require at least a decade to develop today's most advanced SME (such as EUV photolithography tools) with high enough throughput and yield to support mass chip production. However, this timeline depends on actions taken by the United States, its allies, and China.[155]

China could restrict transactions by or impose penalties on non-Chinese firms. In 2020, China introduced an Unreliable Entities List,[156] which Chinese state media claims could be used to restrict trade with or probe U.S. firms, including Qualcomm, Cisco, Apple, and Boeing.[157] (Trade restrictions could include import bans and export controls.) And in 2021, China issued an order allowing Chinese firms, if harmed by firms that obey other nations' extraterritorial laws (such as extraterritorial U.S. export controls), to pursue damages from those firms.[158] But it is unclear whether China will strictly enforce the order. China could also increase regulatory scrutiny of non-Chinese firms; it may already be pursuing antitrust action against Google[159] and may reject the proposed merger between U.S.-based Nvidia and U.K.-based Arm.[160] However, such efforts could drive supply chains away from China—a trend already underway to some degree[161]—harming China's economy and depriving China of a source of technical know-how. Therefore, drastic action by China is unlikely.

Conclusion

Computer chips are the ultimate dual-use technology. They have powered the digital revolution transforming the world and dramatically increasing standard of living since their invention in the mid-20th century. But the most advanced chips also enable new technologies posing immense danger in the 21st century—including advanced AI systems, autonomous weapons, cyberweapons, hypersonics, and the latest generation of nuclear weapons. The United States and allied democracies currently dominate the supply chains to produce these chips, and can thus manage the proliferation of these chips to prevent uses harming international security and human rights. These countries should do just that, while also pursuing policies that maintain control of chip supply chains. If they succeed, democracies can together ensure that advanced chips remain an engine for global innovation, prosperity, and peace.

Appendix A: U.S. Reliance on Chinese imports for Raw Materials

Table 3 shows U.S. import reliance for domestic consumption and China's share of U.S. imports for key primary materials for chip production. Taken together, these metrics roughly quantify U.S. reliance on Chinese imports for domestic consumption.

Table 3: 2015–2018 U.S. reliance on Chinese imports for raw materials[162]

Material	Chinese share of U.S. imports	U.S. net import reliance	Material	Chinese share of U.S. imports	U.S. net import reliance
Aluminum	6%	22%	Magnesium	49%	<50%
Antimony	60%	84%	Molybdenum	<5%	0%
Arsenic	55%	100%	Phosphorus	<1%	10%
Beryllium	<28%	3%	Platinum	<25%	64%
Bismuth	76%	96%	Rare earths	80%	100%
Boron	<4%	0%	Silicon	<30%	41%
Carbon	33%	100%	Silicon carbide	66%	>50%
Cobalt	11%	78%	Sodium chloride	<21%	29%
Copper	<7%	35%	Sulfur	<9%	7%
Fluorine	6%	100%	Tantalum	<37%	100%
Gallium	50%	100%	Tellurium	25%	>95%
Germanium	59%	>50%	Tin	<7%	77%
Gold	<30%	0%	Titanium	13%	0%
Indium	36%	100%	Tungsten[163]	31%	>50%
Lead	<16%	30%	Zinc	<9%	0%
Lithium	3%	>25%	Zirconium	<8%	0%

Appendix B: Identified Chokepoints

Table 4: Identified chokepoints

Category	**Chokepoint**	**Subtype (if any)**	**Minimum viable group of export control partners (all semiconductor-producing nations preferred)**	**China's access currently controlled?[164]**
Materials needed to make chips	Leading-edge photomasks		Japan, U.S., Taiwan, South Korea	Yes for EUV and some chips (e.g. FPGAs)
	EUV and ArFi photoresists		Japan, U.S., South Korea	Yes for EUV
	300 mm silicon wafers		Japan, Taiwan, Germany, South Korea	No
Semiconductor manufacturing equipment	Lithography (chipmaking equipment)	EUV scanners	Netherlands	Yes
		ArFi scanners	Netherlands, Japan	No
		EUV and ArFi resist processing	Japan	No
		Photomask inspection and repair	U.S., Japan, Germany	No
		Nanoimprint lithography	Austria, Japan, U.S., Germany, Sweden	Yes
		Electron-beam lithography	Germany, Japan	Yes
	Lithography (mask-making equipment)		Japan, U.S., Germany	
		Laser lithography	Sweden, Germany	Yes
	Other chipmaking equipment	Atomic layer etching	U.S., Japan, U.K.	No
		Advanced chemical vapor deposition	U.S., Japan, Netherlands, South Korea	Some types
		Advanced ion implanters	U.S., Japan, Taiwan	Some types
		Rapid thermal processing	U.S., Japan, South Korea	No
		Chemical mechanical planarization	U.S., Japan, South Korea	No
		Wafer metrology and inspection	U.S., Japan (optionally Netherlands, Germany, Israel, South Korea, France)	No
	Wafer manufacturing equipment		Japan, Switzerland, Germany, Austria	No
	Test equipment for logic chips		U.S., Japan, Taiwan, Italy	Some types

Fabs	Chips with non-planar processes, e.g. FinFET (typically ≤16 nm)		South Korea, Taiwan, U.S.	Only some chip designs
Chip design	Advanced chip design IP	x86 CPU design IP	U.S.	Yes
		GPU design IP	U.S.	No
		FPGA design IP	U.S.	Yes
		AI training ASIC design IP	U.S., U.K. Israel	Unclear
		Core IP	U.S., U.K.	Only some chip designs
	EDA software (to design chips)		U.S.	No

Appendix C: Key Firms and Revenue Exposure to China

Table 5: Semiconductor firms' market shares and revenue exposure to China

Firm type	**Firm**	**Country**	**Global market share**[165] **(capacity share for fabs**[166]**)**	**Revenue from China (firm-wide unless otherwise noted)**[167]
Semiconductor manufacturing equipment	ASML	Netherlands	17%	15%
	Tokyo Electron	Japan	12%	18%
	Nikon		2%	28%
	Applied Materials	U.S.	18%	29%
	Lam Research		12%	16%
	KLA		6%	16%
Chip design	Arm	U.K.	41% (Core IP)	Unavailable
	Synopsys	U.S.	37% (EDA); 18% (Core IP)	
	Cadence		25% (EDA); 6% (Core IP)	10%
	Mentor Graphics		15% (EDA)	15%
	Ansys		13% (EDA)	4%
	Nvidia		73% (Discrete GPUs)	24%
	AMD		27% (Discrete GPUs); 23% (CPUs)	26%
	Xilinx		53% (FPGAs)	51% (Asia Pacific excluding Japan)
	Intel		36% (FPGAs); 77% (CPUs)	27% (firm-wide); (31% (FPGAs)
Fabs			4%	
	GlobalFoundries		2%	Unavailable
	TSMC	Taiwan	8%	17%
	UMC		3%	12%
	Samsung	South Korea	12%	16%

Appendix D: Advanced Fabs by Location

Table 6: Most advanced ≤45 nm fab by location[168]

Fab location	Firm HQ	Firm	Most advanced node (nm)	Chip type
U.S.	U.S.	Intel	10	Logic (IDM)
		GlobalFoundries	12	Logic (Foundry)
		Micron	20	Memory
	South Korea	Samsung	11	Logic (Foundry)
Taiwan	Taiwan	TSMC	3	
		Nanya	20	Memory
	U.S.	Micron	16	
South Korea	South Korea	Samsung	5	Logic (Foundry)
			10	Memory
Japan	Japan	Renesas	40	Logic (IDM)
	U.S.	Micron	16	Memory
	U.S./Japan	Flash Alliance	15	
	Taiwan	UMC	40	Logic (Foundry)
France	Italy	STMicroelectronics	14	Logic (IDM)
Israel	U.S.	Intel	10	
Ireland			14	
Germany		GlobalFoundries	22	Logic (Foundry)
Singapore			40	
		Micron	20	Memory
	Taiwan	UMC	40	Logic (Foundry)
China	China	SMIC	14	
		CXMT	17	Memory
	U.S.	Intel	20	

	Taiwan	TSMC	16	Logic (Foundry)
	South Korea	SK Hynix	18	Memory

Appendix E: Gross Margin Losses from Export Controls

Gross margin is equal to revenue minus cost of goods sold (which are typically variable costs). Gross margin is allocated to R&D, operating profit, and selling, general and administrative expenses (typically fixed costs). If export controls are applied, a firm would not incur costs of goods sold, so the combination of these savings plus compensation for gross margin would leave the firm in the same position as if export controls were not applied.

Table 7: Gross margin losses from fab equipment export controls[169]

Line	*Line Item*	*Fab equipment*
1	Projected 2021 fab equipment spending in China	$13.2 billion
2	Market share of participating countries	94% (US, JP, NL)
3	**Projected 2021 revenue from China for participating countries (based on lines 1, 2)**	**$12.5 billion**
4	Industry-wide gross margins	45%
5	**Gross margin from China for participating countries (based on lines 3, 4)**	**$5.6 billion**
6	Time of depressed revenue	2 years[170]
7	**Total gross margin losses due to export controls on all fabs in China for participating countries (based on lines 5, 6)**	**$11.2 billion**
8	Projected 2021 fab equipment spending in China from ≤45 nm	72.7%
9	Projected 2021 fab equipment spending in China from ≤28 nm	56.4%
10	Projected 2021 fab equipment spending in China from ≤16 nm	8.2%
11	Projected 2021 fab equipment spending in China from ≤5 nm	0%
12	**Total gross margin losses due to export controls on ≤45 nm fabs in China for participating countries (based on lines 7, 8)**	**$8.2 billion**
13	**Total gross margin losses due to export controls on ≤28 nm fabs in China for participating countries (based on lines 7, 9)**	**$6.3 billion**
14	**Total gross margin losses due to export controls on ≤16 nm fabs in China for participating countries (based on lines 7, 10)**	**$920 million**
15	**Total gross margin losses due to export controls on ≤5 nm fabs in China for participating countries (based on lines 7, 11)**	**Minimal**

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Endnotes

[1] Saif M. Khan, Alexander Mann, and Dahlia Peterson, "The Semiconductor Supply Chain: Assessing National Competitiveness" (Washington, DC: Center for Security and Emerging Technology, January 2021).

[2] These functions are separated in different firms, except with integrated device manufacturers (IDMs), most notably Intel and Samsung, who perform chip design, fabrication, assembly, packaging, and testing. Otherwise, chip design occurs in "fabless" firms that send their designs to fabs called "foundries" that provide contract manufacturing (also called foundry services). "Outsourced semiconductor assembly and test" (OSAT) firms then perform assembly, testing, and packaging.

[3] "World Fab Forecast" (Milpitas, CA: SEMI, November 2020 edition); Antonio Varas, Raj Varadarajan, Jimmy Goodrich, and Falan Yinug, "Government Incentives and US Competitiveness in Semiconductor Manufacturing" (Boston Consulting Group and Semiconductor Industry Association, September 2020), 7, https://www.semiconductors.org/wp-content/uploads/2020/09/Government-Incentives-and-US-Competitiveness-in-Semiconductor-Manufacturing-Sep-2020.pdf.

[4] Items are more robust chokepoints if they are (1) tangible and difficult to steal or copy, (2) expensive, (3) dependent on talent requiring implicit know-how to produce; and (4) produced by a small number of suppliers, especially because of natural economic forces such as high capital barriers to entry and economies of scale.

[5] Khan et al., "The Semiconductor Supply Chain."

[6] Saif M. Khan and Carrick Flynn, "Maintaining China's Dependence on Democracies for Advanced Computer Chips" (Washington, DC: Brookings Institution & Center for Security and Emerging Technology, April 2020), 11 (endnote 21), https://cset.georgetown.edu/wp-content/uploads/Khan-Flynn%E2%80%94Maintaining-Chinas-Dependence-on-Democracies.pdf.

[7] At $312.7 billion in 2018, chips are China's top imports. Comtrade database, HS code 8542, accessed July 16, 2020, https://comtrade.un.org/. However, one estimate suggests that China's 2018 chip market was $155.1 billion out of a global $421.7 market. "Can We Believe The Hype About China's Domestic IC Production Plans?," *IC Insights*, June 13, 2019, https://www.icinsights.com/news/bulletins/Can-We-Believe-The-Hype-About-Chinas-Domestic-IC-Production-Plans/. Another estimate suggests that counting only domestically consumed chips—and not those packaged in devices and re-exported—China consumes only 20 percent of the world's chips. This would bring China's yearly chip consumption to less than $100 billion. Dan Kim and John VerWey, "The Potential Impacts of the Made in China 2025 Roadmap on the Integrated Circuit Industries in the U.S., EU and Japan" (Washington, DC: U.S. International Trade Commission, August 2019), 23,

https://www.usitc.gov/publications/332/working_papers/id_19_061_china_integrated_circuits_technology_roadmap_final_080519_kim_verwey-508_compliant.pdf.

[8] Saif M. Khan and Alexander Mann, "AI Chips: What they Are and Why They Matter" (Washington, DC: Center for Security and Emerging Technology, April 2020), 24–25, https://cset.georgetown.edu/wp-content/uploads/AI-Chips%E2%80%94What-They-Are-and-Why-They-Matter.pdf.

[9] Yuan Gao, "China Is Raising Up to $31.5 Billion to Fuel Chip Vision," *Bloomberg*, March 1, 2018, https://www.bloomberg.com/news/articles/2018-03-01/china-is-said-raising-up-to-31-5-billion-to-fuel-chip-vision.

[10] "China IC Ecosystem Report" (Milpitas, CA: SEMI, 2018 edition)

[11] Khan et al., "Maintaining China's Dependence," 1.

[12] That is, China's demand for chips is inelastic to the source—domestic vs. foreign—from which they buy the chips. Relatedly, China's demand for chips should exhibit low price-elasticity of demand, meaning that any increased chip prices due to trade distortions would have only a small impact on China's demand for chips. Jeffrey Ding and Allan Dafoe, "The Logic of Strategic Assets: From Oil to Artificial Intelligence," January 9, 2020, https://arxiv.org/abs/2001.03246.

[13] "Beyond Borders: The Global Semiconductor Value Chain" (San Jose, CA: Semiconductor Industry Association, May 2016), https://www.semiconductors.org/wp-content/uploads/2018/06/SIA-Beyond-Borders-Report-FINAL-May-6-1.pdf.

[14] Khan et al., "Maintaining China's Dependence," 6.

[15] SEMI, "World Fab Forecast," November 2020 edition.

[16] Ian King, "Intel Plunges as It Weighs Exit From Manufacturing Chips," *Bloomberg*, July 23, 2020, https://www.bloomberg.com/news/articles/2020-07-24/intel-considers-what-was-once-heresy-not-manufacturing-chips.

[17] Kristen Baldwin, "DoD Electronics Priorities," NDIA Electronics Division Kickoff Meeting, Arlington, VA, January 18, 2018, 4, https://www.ndia.org/-/media/sites/ndia/divisions/electronics/past-proceedings/ndia-ed-baldwin-18jan2018-vf.ashx.

[18] Mark Lapedus, "A Crisis In DoD's Trusted Foundry Program?," *Semiconductor Engineering*, October 22, 2018, https://semiengineering.com/a-crisis-in-dods-trusted-foundry-program/.

[19] "TSMC Announces Intention to Build and Operate an Advanced Semiconductor Fab in the United States," *TSMC*, May 15, 2020, https://pr.tsmc.com/english/news/2033.

[20] Asa Fitch, Kate O'Keeffe and Bob Davis, "Trump and Chip Makers Including Intel Seek Semiconductor Self-Sufficiency," *The Wall Street Journal*, May 11, 2020, https://www.wsj.com/articles/trump-and-chip-makers-including-intel-seek-semiconductor-self-sufficiency-11589103002.

[21] Adam A. Scher and Peter L. Levin, "Imported Chips Make America's Security Vulnerable," *The Wall Street Journal*, May 25, 2020, https://www.wsj.com/articles/imported-chips-make-americas-security-vulnerable-11590430851.

[22] Saif M. Khan, "U.S. Semiconductor Exports to China: Current Policies and Trends" (Washington, DC: Center for Security and Emerging Technology, October 2020), https://cset.georgetown.edu/research/u-s-semiconductor-exports-to-china-current-policies-and-trends/.

[23] SME includes fab equipment (known in the industry as wafer fab equipment) and equipment for assembly, testing, and packaging. Fab equipment includes chipmaking equipment (known in the industry as wafer processing equipment) and other SME used to make inputs to chips. These other SME include wafer manufacturing equipment, electron-beam lithography tools, laser lithography tools, and ion-beam lithography tools.

[24] For a list of nodes, see "Technology Node," Wikichip, accessed July 16, 2020, https://en.wikichip.org/wiki/technology_node.

[25] Vu Luong, "EUV Lithography Coming to your local IC manufacturer! Soon," *Interuniversity Microelectronics Centre*, May 16, 2018, 13, https://eng.kuleuven.be/en/research/phd/arenberg-youngster-seminars/ays-pdf/20180516-luong-ays-final.pdf. Chipmakers began using ArF immersion photolithography at ≤45 nm nodes, except Intel, which extended ArF dry photolithography to its 45 nm node using double patterning and other process improvements. Chris Auth et al., "45nm High-k + Metal Gate Strain-Enhanced Transistors," *Symposium on VLSI Technology Digest of Technical Papers*, 2008, 128–129, https://download.intel.com/pressroom/kits/advancedtech/pdfs/VLSI_45nm_HiKMG-paper.pdf; Mark LaPedus, "LITHOGRAPHY: AMD preps to take immersion plunge at 45 nm," *EETimes*, December 28, 2006, https://www.eetimes.com/lithography-amd-preps-to-take-immersion-plunge-at-45-nm/.

[26] By the 28 nm node, major chipmakers adopted "high-k" dielectrics to prevent current leakage. Intel was an exception, introducing this material at its 45 nm node. Mark T. Bohr, Robert S. Chau, Tahir Ghani and Kaizad Mistry, "The High-k Solution," *IEEE*, October 1, 2007, https://spectrum.ieee.org/semiconductors/design/the-highk-solution.

[27] By the 14 nm node, all chipmakers adopted a non-planar transistor structure called the FinFET: TSMC (introduced at 16 nm), Samsung (14 nm), GlobalFoundries (14 nm), SMIC (14 nm), and Intel (22 nm, equivalent in specifications of other fabs' 16/14 nm nodes).

[28] Luong, "EUV Lithography." TSMC used ArF immersion photolithography when it initially introduced its 7 nm node, but later used EUV photolithography in conjunction with ArF immersion for an advanced version of its 7 nm node. TSMC exclusively uses EUV at 5 nm. Samsung uses EUV at 7 nm, and Intel plans to use it at 7 nm.

[29] Khan et al., "AI Chips," 24–25.

[30] SEMI, "World Fab Forecast," November 2020 edition. See Table 7 in Appendix E for related analysis.

[31] Khan, "U.S. Semiconductor Exports to China."

[32] For a list of non-Chinese fabs in China, see Khan et al., "Maintaining China's Dependence," 14 (endnote 52).

[33] In response to unilateral U.S. export controls, China could turn to imports from U.S. allies. When the United States applied unilateral export controls to satellites, non-U.S. allies began producing satellites for customers U.S. satellite firms could not serve. Bureau of Industry and Security, *U.S. Space Industry "Deep Dive" Assessment: Impact of U.S. Export Controls on the Space Industrial Base* (Washington, DC: Department of Commerce, February 2014), 30, https://www.bis.doc.gov/index.php/documents/technology-evaluation/898-space-export-control-report/file.

[34] In response to the U.S. entity listing of China's National Supercomputing Centers to prevent their purchase of Intel chips, these centers instead purchased Chinese-designed CPUs that were possibly also manufactured in China. Brian Barrett, "China's New Supercomputer Puts the US Even Further Behind," *Wired*, June 21, 2016, https://www.wired.com/2016/06/fastest-supercomputer-sunway-taihulight/.

[35] Antonio Varas and Raj Varadarajan, "How Restricting Trade with China Could End US Semiconductor Leadership" (Boston Consulting Group, March 9, 2020), https://www.bcg.com/publications/2020/restricting-trade-with-china-could-end-united-states-semiconductor-leadership.aspx. This analysis assumes U.S. controls are unilateral, but includes applications of U.S. re-export controls governed by the de minimis rule and the foreign-produced direct product rule.

[36] Lam Research, "Comment on Advanced Notice of Proposed Rulemaking Regarding Review of Controls for Certain Emerging Technologies," February 22, 2019, 6, https://www.regulations.gov/document?D=B IS-2018-0024-0206.

[37] For a similar industry proposal, see Semiconductor Industry Association, "Comments of the Semiconductor Industry Association on Advanced Notice Regarding the Identification and Review of Controls for Certain Foundational Technologies," November 9, 2020, 27–28, https://www.semiconductors.org/wp-content/uploads/2020/11/SIA-Foundational-Comments-11-9-20.pdf. The Multilateral Action on Sensitive Technologies effort by the U.S. State Department is a promising effort. Christopher Ashley Ford, "Huawei and Its Siblings, the Chinese Tech Giants: National Security and Foreign Policy Implications," *U.S. Department of State*, September 11, 2019, https://www.state.gov/huawei-and-its-siblings-the-chinese-tech-giants-national-security-and-foreign-policy-implications/.

[38] For example, the United States should use the de minimis and/or foreign-produced rule to ensure U.S. firms' SME produced abroad is also covered by U.S. controls. Singapore in particular is a major SME exporter. Chad P. Bown, "How the United States marched the semiconductor industry into its trade war with China" (Washington, DC: Peterson Institute for International Economics, December 2020), 27, https://www.piie.com/sites/default/files/documents/wp20-16.pdf.

[39] For example, the Commerce Control List controls currently-listed SME in many ways. SME is controlled to China under ECCN 3B001, 3B002, and 3B611. Software used with or used to develop SME are controlled to China under ECCN 3D001-005 and 3D611. Technical data relating to SME and supporting software are controlled to China under ECCN 3E001 and 3E002.

[40] Protecting U.S. and allied advantages in advanced lithography equipment may pay dividends beyond currently existing computing paradigms. Many emerging technologies may include small features requiring advanced lithography equipment. For example, producing some quantum computers may require lithography. Fernando Gonzalez-Zalba, Tsung-Yeh Yang and Alessandro Rossi, "Manufacturing silicon qubits at scale," *Physics World*, November 12, 2019, https://physicsworld.com/a/manufacturing-silicon-qubits-at-scale/https://physicsworld.com/a/manufacturing-silicon-qubits-at-scale/.

[41] For additional potential chipmaking equipment chokepoints, see Table 4.

[42] Some vendors produce stand-alone atomic layer etching tools. But other vendors integrate atomic layer etching technology into their reactive ion etching tools. Mark LaPedus, "Atomic Layer Etch Expands To New Markets," *Semiconductor Engineering*, July 16, 2020, https://semiengineering.com/atomic-layer-etch-expands-to-new-markets/. This integration presents a problem if export controls cause the latter vendors to lose sales of reactive ion etching tools to competitors, including China's AMEC, which produces advanced reactive ion etching tools. Ideally, export controls should prompt vendors to create separate tools for atomic layer etching and reactive ion etching tools.

[43] Throughout, the term "photomask" is intended to additionally include reticles. A photomask's pattern has a 1:1 correspondence to a desired wafer pattern, while a reticle's pattern corresponds to only part of a desired wafer pattern. Therefore, the reticle must be

moved relative to the wafer to transfer the reticle's pattern multiple times to create a repeating pattern on the wafer.

[44] As discussed in endnote 25, chipmakers began using ArF immersion photolithography at ≤45 nm nodes, except Intel, which extended ArF dry photolithography to its 45 nm node. EUV and ArF immersion scanners are also backward compatible with older nodes. However, less advanced photolithography tools, such as dry ArF, krypton fluoride, and i-line tools, also support these nodes.

[45] Alexandra Alper, Toby Sterling, and Stephen Nellis, "Trump administration pressed Dutch hard to cancel China chip-equipment sale: sources," *Reuters*, January 6, 2020, https://www.reuters.com/article/us-asmlholding-usa-china-insight-idUSKBN1Z50HN.

[46] ASML's U.S. subsidiary Cymer produces a light source used in ASML's photolithography equipment. Japanese firm Gigaphoton also develops advanced light sources. ASML's photolithography tools also rely on mirrors from German firm Carl Zeiss and lasers from German firm TRUMPF. "ZEISS and ASML strengthen partnership for next generation of EUV Lithography due in early 2020s," *ASML*, November 3, 2016, https://www.asml.com/en/news/press-releases/zeiss-and-asml-strengthen-partnership-for-next-generation-of-euv-lithography-(54430); "Generation of EUV radiation using a CO2 high-power laser system and tin," TRUMPF, accessed July 16, 2020, https://www.trumpf.com/en_US/applications/euv-lithography/. U.S. Commerce Control List and the Wassenaar Arrangement already lists "specially designed components" of EUV tools under ECCN 3B001 and Section 3.B.1, respectively. The United States and other Wassenaar members should interpret these provisions to cover EUV light sources, mirrors, and laser amplifiers.

[47] The low throughput of electron-beam and laser lithography preclude use for high-volume chip production.

[48] For now, nanoimprint lithography experiences problems with yields and throughput and is used mostly for non-semiconductor applications. Mark LaPedus, "What Happened To Nanoimprint Litho?," *Semiconductor Engineering*, March 19, 2018, https://semiengineering.com/what-happened-to-nanoimprint-litho.

[49] Even without Dutch participation, the U.S. and/or Germany could control re-exports of EUV tools by controlling EUV components—including light sources, mirrors, and laser amplifiers—under the de minimis rule. For details on EUV components, see endnote 46.

[50] The United States and Japan have a history of cooperation on the U.S.-Japan supercomputer agreement, which they can use as a template for future cooperation. Glenn J. McLoughlin and Ian F. Fergusson, "High Performance Computers and Export Control Policy: Issues for Congress" (Washington, DC: Federation of American Scientists, February 10, 2003), https://fas.org/sgp/crs/RL31175.pdf.

[51] James A. Lewis, "Managing Semiconductor Exports to China," *Center for Strategic and International Studies*, May 5, 2020, https://www.csis.org/analysis/managing-semiconductor-exports-china.

[52] In reality, Dutch and Japanese export controls on photolithography equipment would render complementary U.S. SME useless in advanced Chinese fabs, so China would therefore reduce imports of U.S. SME as well.

[53] "First China-made 28nm lithography machine expected to be delivered in 2021-2022," *cnTechPost*, June 5, 2020, https://cntechpost.com/2020/06/05/first-china-made-28nm-lithography-machine-expected-to-be-delivered-in-2021-2022/; "600 series lithography machine-IC front manufacturing," Shanghai Microelectronics Equipment, accessed July 16, 2020,
http://www.smee.com.cn/eis.pub?service=homepageService&method=indexinfo&onclicknodeno=1_4_4_1.

[54] ASML's EUV technology became viable for mass production in 2020, a decade after ASML sold its first EUV tool in 2010. "A backgrounder on Extreme Ultraviolet (EUV) lithography," *ASML*, January 18, 2018 https://medium.com/@ASMLcompany/a-backgrounder-on-extreme-ultraviolet-euv-lithography-a5fccb8e99f4.

[55] Will Hunt, Saif M. Khan, and Dahlia Peterson, "China's Progress in Semiconductor Manufacturing Equipment: Accelerants and Policy Implications" (Washington, DC: Center for Security and Emerging Technology, forthcoming).

[56] Electron-beam lithography tools are the dominant tools for mask-making, with laser lithography tools a distant second. Ion-beam lithography tools are currently rarely used for mask-making. Therefore, for certain types of photomasks, controlling only some types of these tools (especially electron-beam lithography tools) may be necessary.

[57] Shannon Davis, "EUV Materials Small But Strategic Fraction of $1.6B IC Photoresists Market," *Semiconductor Digest*, March 11, 2020, https://www.semiconductor-digest.com/2020/03/11/euv-materials-small-but-strategic-fraction-of-1-6b-ic-photoresists-market/.

[58] Chinese semiconductor sectors besides fabs would be less affected by SME and materials export controls. Chinese design firms could still design leading-edge chips for fabrication at foreign fabs such as TSMC. For this reason, China's EDA software sector would also likely not be significantly impacted. China's OSAT firms could lose business from locally produced chips, but retain a comparative advantage in ATP for chips fabricated outside China.

[59] This outcome could only occur if technical data related to SME is controlled; otherwise, U.S., Japanese, and Dutch SME firms could offer repair services to Chinese fabs. End of life of all controlled SME may take time, as the Chinese fabs are stockpiling imports of SME. This is clear as China imports more SME from the United States than Taiwan despite having far

less fab capacity than Taiwan. "Economics and Trade Bulletin," (Washington, DC: U.S.-China Economic and Security Review Commission, January 11, 2019), 9, https://www.uscc.gov/sites/default/files/Research/January%202019%20Trade%20%20Bulletin.pdf.

[60] China's most advanced chipmaker, SMIC, reported that it gained only 1.3 percent of its revenues from its 14 nm node and 6.5 percent from its 28 nm node in the first quarter of 2020. "SMIC Q1 2020 Financial Presentation," *SMIC*, May 2020, https://www.smics.com/uploads/Q1_2020%20Financials-2.pdf. However, the former percentage may expand now that Huawei is placing 14 nm orders at SMIC.

[61] The Soviet Union represents a historical case where SME export controls could have succeeded had they been enforced more strictly. In 1986, the Central Intelligence Agency estimated that without access to Western semiconductor technology, the Soviet Union's eight-to-nine-year lag in chip development would have increased by an additional decade and their production of small to medium chips would have been reduced by 75 percent and large chips by 90 percent or more. The CIA also estimated that between the early 1970s and 1986, the Soviet Union spent $2 billion to acquire over 3,000 pieces of Western SME, enough to outfit 24 fabs. The CIA also estimated Soviet chip production at roughly 10 percent of US production, with Western SME providing up to a third of Soviet production needs. *Soviet Microelectronics: Impact of Western Technology Acquisitions: An Intelligence Assessment* (Langley, VA: Central Intelligence Agency, December 1986), https://www.cia.gov/library/readingroom/docs/DOC_0000499603.pdf.

[62] Japanese export controls on photoresists, hydrogen fluoride, and fluorinated polyimide to South Korea in July 2019 put Samsung's fabs in jeopardy. Samuel M. Goodman, Dan Kim, and John VerWey, *The South Korea-Japan Trade Dispute in Context: Semiconductor Manufacturing, Chemicals, and Concentrated Supply Chains* (Washington, DC: U.S. International Trade Commission, October 2019), https://usitc.gov/publications/332/working_papers/the_%20south_korea-japan_trade_dispute_in_context_semiconductor_manufacturing_chemicals_and_concentrated_%20supply_chains.pdf. In December 2019, Japan withdrew export controls on photoresists. Ritsuko Shimizu, Makiko Yamazaki, and Hyunjoo Jin, "Japan partially reverses curbs on tech materials exports to South Korea," *Reuters*, December 20, 2019, https://www.reuters.com/article/us-southkorea-japan-idUSKBN1YO11L. Additionally, South Korean firms are developing homegrown replacements and finding alternative foreign suppliers for hydrogen fluoride. Stephen Ezell, "Understanding the South Korea-Japan Trade Dispute and Its Impacts on U.S. Foreign Policy," *Information Technology & Innovation Foundation*, January 16, 2020, https://itif.org/publications/2020/01/16/understanding-south-korea-japan-trade-dispute-and-its-impacts-us-foreign; Kotaro Hosokawa and Ten Umekuni, "Korea Inc. ditches Japan chipmaking materials for homegrown supply," *Nikkei Asia*, May 23, 2020, https://asia.nikkei.com/Spotlight/Japan-South-Korea-rift/Korea-Inc.-ditches-Japan-chipmaking-materials-for-homegrown-supply. The export controls coincided with South Korean chip firms' market share dropping from 24 percent to 19 percent between 2018 and

2019. "2020 SIA Factbook" (San Jose, CA: Semiconductor Industry Association, 2020), 3, https://www.semiconductors.org/wp-content/uploads/2020/04/2020-SIA-Factbook-FINAL_reduced-size.pdf. However, that decline was largely due to a drop in memory chip prices in 2019.

[63] This is because of economies of scale, rising fixed costs, IP moats, and clustering of talent and know-how.

[64] In September 2020, the U.S. government notified U.S. SME firms that exports to SMIC require an export license under military end-use and end-user export controls, because it sells chips to the Chinese military. Dan Strumpf, "U.S. Sets Export Controls on China's Top Chip Maker," *The Wall Street Journal*, September 28, 2020, https://www.wsj.com/articles/u-s-sets-export-controls-onchinas-top-chip-maker-11601118353; see Alexandra Alper and Humeyra Pamuk, "Exclusive: Trump to add China's SMIC and CNOOC to defense blacklist – sources," *Reuters*, November 29, 2020, https://www.reuters.com/article/us-usa-china-military-companies-exclusiv-idUSKBN28A036. In December 2020, the U.S. government added SMIC to the entity list, imposing a "presumption of denial" licensing standard for exports of SME "uniquely required" to make ≤10 nm chips and a "case-by-case" licensing standard for other exports. "Commerce Adds China's SMIC to the Entity List, Restricting Access to Key Enabling U.S. Technology," *U.S. Department of* Commerce, December 18, 2020, . However, the "case-by-case" standard—under which licenses are typically approved—applies to nearly all ≤10 nm U.S. SME, as it is typically used for 14 nm chips.

[65] Douglas B. Fuller, *Paper Tigers, Hidden Dragons: Firms and the Political Economy of China's Technological Development* (Oxford: Oxford University Press, 2016), 118, 156; Douglas B. Fuller, "Growth, Upgrading, and Limited Catch-Up in China's Semiconductor Industry," in *Policy, Regulation and Innovation in China's Electricity and Telecom Industries*, eds. Loren Brandt and Thomas G. Rawski (Cambridge: Cambridge University Press, 2019), 262–303, https://doi.org/10.1017/9781108645997.007.

[66] In response to the Dutch government's non-renewal of an export license for EUV photolithography equipment to China, ASML's CEO Peter Wennink predicted this effect, saying "if we cannot ship to customer A or country B, we'll ship it to customer C and country D" to meet global chip demand. Toby Sterling, "ASML sees no impact from China trade war, good growth in 2020," *Yahoo News*, January 22, 2020, https://www.yahoo.com/news/asml-sees-no-impact-china-144103191.html.

[67] In the short term, the degree of elasticity of supply for chips is uncertain. Elasticity of supply would be high and therefore chip prices would remain stable if fabs outside China are able to quickly ramp up production to serve demand that would otherwise be served by Chinese fabs. Non-Chinese fabs could achieve this if they are not already operating at peak capacity and could scale up production with existing facilities, SME, and workers. By contrast, elasticity of supply would be low and therefore chip prices would increase if fabs outside China were already at peak capacity. In this scenario, increasing chip prices would

incentivize fabs outside China to invest in additional facilities and SME and to hire new workers. This process could take years. But in the long term, elasticity of supply is high, as non-Chinese fabs would eventually expand capacity to meet chip demand.

[68] In economics, the "beggar-thy-neighbor" strategy involves using trade restrictions to benefit a country's domestic economy at the expense of a competitor's economy. In the long-term, this strategy can result in tit-for-tat trade restrictions that prevent these countries from jointly benefitting from positive-sum trade. Chad P. Bown, "Export Controls: America's Other National Security Threat" (Washington, DC: Peterson Institute for International Economics, May 2020), 14–16, https://www.piie.com/system/files/documents/wp20-8.pdf.

[69] "An imitator must possess an adequate absorptive capacity: material and nonmaterial capabilities such as laboratories, research centers, testing and production facilities, a skilled workforce, and a cumulative technological knowledge base (the stock of knowledge acquired through previous projects)." Andrea Gilli and Mauro Gilli, "Why China Has Not Caught Up Yet: Military-Technological Superiority and the Limits of Imitation, Reverse Engineering, and Cyber Espionage," *International Security* 43, no. 3 (February 15, 2019): 141-189, https://www.mitpressjournals.org/doi/full/10.1162/isec_a_00337.

[70] The world's most advanced fabs today cost tens of billions of dollars to build. "A look inside the factory around which the modern world turns," *The Economist*, December 18, 2019, https://www.economist.com/christmas-specials/2019/12/18/a-look-inside-the-factory-around-which-the-modern-world-turns.

[71] The historical case of the F-22 is instructive. In 2011, the United States stopped manufacturing the F-22, and in 2017, found that restarting production would cost $10 billion, "equivalent to 25 percent of the total procurement cost for 194 aircraft." Gilli et al., "Why China Has Not Caught Up Yet."

[72] The top producer besides the United States is Japan, while others with fledgling industries are the United Kingdom, Israel, and China. Khan et al., "The Semiconductor Supply Chain."

[73] Many legacy software systems throughout the world, including in China, were designed to run on Intel and AMD CPUs based on the x86 architecture. By contrast, Chinese CPUs relying on different architectures cannot be used with these legacy software systems, presenting an uphill battle for Chinese chip designers.

[74] China is attempting to acquire IP and know-how for dominant U.S. architectures to replace U.S. chips even for legacy systems. For example, in 2016, Chinese supercomputer developer Sugon obtained partnered with AMD to design chips using AMD's x86 CPU design. Kate O'Keeffe and Brian Spegele, "How a Big U.S. Chip Maker Gave China the 'Keys to the Kingdom'," *The Wall Street Journal*, June 27, 2019, https://www.wsj.com/articles/u-s-tried-to-stop-china-acquiring-world-class-chips-china-got-them-anyway-11561646798. However, industry insiders claim ADM gave away little IP or know-how. Stewart Randall, "Did AMD really give away 'keys to the kingdom'?," *TechNode*, July 10, 2019,

https://technode.com/2019/07/10/did-amd-really-give-away-keys-to-the-kingdom/. And Chinese chip designer Zhaoxin has also separately developed x86 CPUs in a joint venture with Taiwanese chip designer VIA Technologies, which has long been a minor player on the x86 market. Paul Alcorn, "Zhaoxin KaiXian x86 CPU Tested: The Rise of China's Chips," *Tom's Hardware*, April 10, 2020, https://www.tomshardware.com/features/zhaoxin-kx-u6780a-x86-cpu-tested.

[75] Chinese chip designers are attempting to create alternative chip architecture ecosystems, which could spur Chinese software developers to adapt their software to them. For example, Chinese chip designers have developed high-end chips based on licensed Arm architectures and are exploring development and adoption of the open-source architectures RISC-V and MIPS, but success could take years. Joel Hruska, "Cut Off From ARM, x86, What CPU Architectures Can Huawei Use?," *ExtremeTech*, May 23, 2019, https://www.extremetech.com/computing/291875-cut-off-from-arm-x86-what-cpu-architectures-can-huawei-actually-use; "A new blueprint for microprocessors challenges the industry's giants," *The Economist*, October 3, 2019, https://www.economist.com/science-and-technology/2019/10/03/a-new-blueprint-for-microprocessors-challenges-the-industrys-giants.

[76] If Chinese consumers opt for commodity chips rather than bespoke chips requiring new designs, EDA firms could suffer revenue harms, resulting in fewer completed designs per year. For example, a general-purpose chip based on a single design may sell millions, while an ASIC may sell only thousands.

[77] While EDA controls could boost U.S. and allied chip design revenues, export controls on chip design IP could reduce their licensing revenues.

[78] EDA firms often sell easily pirated "on-premise" software (i.e., installed on customers' networks), potentially rendering EDA software controls ineffective. EDA software is typically licensed to a specific number of design engineers. Synopsis, "Form 10-K," October 31, 2019, 10, https://www.synopsys.com/content/dam/synopsys/company/investor-relations/10k/form10k-2019.pdf; Clair Brown and Greg Linden, Chips and Change: How Crisis Reshapes the Semiconductor Industry (Cambridge, MA: MIT Press, August 19, 2011), 12. EDA piracy is rampant in China, particularly for locally manufactured chips. Steward Randall, "SILICON | Why Chinese EDA tools lag behind," November 13, 2019, *TechNode*, https://technode.com/2019/11/13/silicon-why-chinese-eda-tools-lag-behind/. Export controls could increase piracy. However, foreign fabs may decline business from Chinese design firms using pirated EDA, given the legal risks. Cheng Ting-Fang and Laury Li, "Huawei loses access to vital chip design updates from Synopsys," *Nikkei Asia*, May 31, 2019, https://asia.nikkei.com/Spotlight/Huawei-crackdown/Huawei-loses-access-to-vital-chip-design-updates-from-Synopsys; Stewart Randall, "SILICON | China's design tools conundrum," *TechNode*, November 7, 2019, https://technode.com/2019/11/07/silicon-chinas-design-tools-conundrum/. Regardless

of the viability of export controls, the U.S. government could encourage EDA firms to provide EDA tools over the cloud—with datacenters located in the United States—to reduce piracy.

[79] Chinese chip designers obtain about 60 percent of their revenue from ≤45 nm nodes, 45 percent from ≤28 nm nodes, about 25 percent from ≤16 nm nodes, and about 5 percent from ≤7 nm nodes. "Global Manufacturing Market Tracker," IHS Markit, September 2019, https://ihsmarkit.com/products/global-manufacturing-market-tracker.html.

[80] EDA upgrades are increasingly adding AI-specific chip design tools.

[81] Randall, "Why Chinese EDA tools lag behind"; "Current Status of the Integrated Circuit Industry in China," *J. Microelectron. Manuf.* 2, no. 19020305 (2019), 3, http://www.jommpublish.org/static/publish/33/12/D9/CA33624FE28386D91FC4BF209E/10.33079.jomm.19020305.pdf.

[82] The U.S. Department of Defense consumes less than 1 percent of global chip output, down from over 50 percent in the mid-1960s. Daniel J. Radack, Brian S. Cohen, Robert F. Leheny, Vashisht Sharma, and Marko M.G. Slusarczuk, "Semiconductor Industrial Base Focus Study – Final Report" (Institute for Defense Analyses, December 2016), 1-1, https://www.ida.org/-/media/feature/publications/s/se/semiconductor-industrial-base-focus-study--final-report/d-8294.ashx. The Chinese military and affiliated entities are unlikely to consume much more than this.

[83] This should also capture Chinese affiliates of U.S., Taiwanese, and South Korean chipmakers. If these affiliates do not follow chip export controls, they could be denied access to SME and materials, as discussed earlier.

[84] Alternatively, an equivalent of the U.S. de minimis rule could be used. TSMC reportedly found that its 7 nm node uses nine to 10 percent U.S.-origin content—counting U.S. SME, EDA, and IP— while its 14 nm node uses 15 percent. Non-U.S. origin content includes Taiwanese labor, non-U.S. SME, and wafers from Japan, Europe and Taiwan, among other content. "U.S. plans to further restrict Huawei: TSMC's 14nm process may be cut off," *Sina Finance*, December 23, 2019, https://finance.sina.cn/stock/relnews/us/2019-12-23/detail-iihnzahi9455436.d.html; Dieter Ernst, "Competing in Artificial Intelligence Chips: China's Challenge amid Technology War" (Centre for International Governance Innovation, 2020), 38, https://www.cigionline.org/sites/default/files/documents/Competing%20in%20Artifical%20Intelligence%20Chips%20-%20Dieter%20Ernst_web.pdf.

[85] As sole producers of advanced photolithography equipment, the Netherlands and Japan could attempt to collaborate, but could find enforcement difficult without U.S. backing.

[86] Addition of Huawei Non-U.S. Affiliates to the Entity List, the Removal of Temporary General License, and Amendments to General Prohibition Three (Foreign-Produced Direct Product Rule), 85 Fed. Reg. 51,596 (August 17, 2020) (revising 15 C.F.R. § 736, 744, and

762), https://www.federalregister.gov/documents/2020/08/20/2020-18213/addition-of-huawei-non-us-affiliates-to-the-entity-list-the-removal-of-temporary-general-license-and.

[87] Cheng Ting-Fang and Laury Li, "TSMC plans to halt chip supplies to Huawei in 2 months," *Nikkei Asia*, July 16, 2020, https://asia.nikkei.com/Spotlight/Huawei-crackdown/TSMC-plans-to-halt-chip-supplies-to-Huawei-in-2-months.

[88] If Japan does join the United States in applying the foreign-produced direct product rule, Japanese firms may attempt to produce replacement SME. Douglas B. Fuller, "Cutting Off Our Nose to Spite Our Face" (Laurel, MD: Johns Hopkins Applied Physics Laboratory, October 2020), https://www.jhuapl.edu/assessing-us-china-technology-connections/dist/2fe619b308e5da011213dae5f2f2c483.pdf. However, given U.S. firms' dominance in many sectors, such as metrology and inspection tools, replacing U.S. SME will be a tall order for the next decade. Therefore, narrow use of the foreign-produced direct product rule keep risks of this outcome low. Overzealous application could result in a scenario like the historical case of non-U.S. suppliers producing "ITAR-free" defense articles with no U.S. content to evade broad U.S. export controls on satellites. Scott Jones, "A slippery slope: Will foreign companies start ditching American dual-use tech?," *Defense News*, January 22, 2020, https://www.defensenews.com/opinion/commentary/2020/01/22/a-slippery-slope-will-foreign-companies-start-ditching-american-dual-use-tech/.

[89] The U.S. origin content counts toward the threshold percentage if the item is a (1) non-U.S.-made tangible item that "incorporates" the content, where that content is a controlled U.S.-origin tangible item, (2) non-U.S.-made tangible item that is "bundled" with the content, where that content is controlled U.S.-origin software, (3) non-U.S.-made software that "incorporates" the content, where that content is controlled U.S.-origin software, or (4) non-U.S.-made technical data that is "commingled with or drawn from" the content, where that content is controlled U.S.-origin technical data. 15 C.F.R. § 734.4 (2019); 15 C.F.R. Supplement No. 2 to § 734 (2019); Bureau of Industry and Security, "De minimis Rules and Guidelines," November 5, 2019, https://www.bis.doc.gov/index.php/documents/pdfs/1382-de-minimis-guidance/file.

[90] These chips are listed under ECCN 3A001 and 3A611.

[91] On an industry-wide level, chip design activities—which produce the exported IP—account for well over 25 percent of a chip's value. Khan et al., "The Semiconductor Supply Chain."

[92] AI chips follow the logic of strategic dependency where "a concentration of foreign suppliers impose a negative externality for the importing state, represented by the potential economic and security costs of being cut off from accessing these items," where such assets have "low price-elasticity" of both supply and demand, and "broad, ongoing flows." Ding et al., "The Logic of Strategic Assets." Another model terms this dynamic "weaponized interdependence," where a state with political authority over central nodes of international

networks designed to generate market efficiencies is deployed to choke off adversaries from economic and information flows. Henry Farrell and Abraham L. Newman, "Weaponized Interdependence," *International Security* 44, no. 1 (Summer 2019): 5, 18, https://www.mitpressjournals.org/doi/full/10.1162/isec_a_00351.

[93] Advanced AI chips are typically fabricated at ≤16 nm nodes to achieve competitive performance and cost-effectiveness. Khan et al., "AI Chips," 24–25, 28–29. Therefore, an appropriate threshold could be to monitor or control chips with non-planar transistors, as TSMC and Samsung respectively began using the FinFET (the most common non-planar transistor) for their 16 nm and 14 nm nodes. Intel began using the FinFET for its 22 nm node, which has similar specifications as TSMC's 16 nm node. At less advanced nodes, transistors are planar. Future nodes, such as Samsung's 3 nm node, are expected to use a new type of non-planar transistor called the gate-all-around FET.

[94] Only clusters of server-grade chips achieve the necessary performance for training advanced AI systems. Therefore, controlling less powerful consumer AI chips—such as those in smartphones—is unnecessary. (Firms including Samsung (South Korea) and MediaTek (Taiwan), which both license IP cores from ARM (U.K.), design systems-on-chips with AI cores for smartphones.) An appropriate threshold could be to monitor or control chips exceeding a performance threshold met only by server-grade chips.

[95] The cost-effectiveness and speed of AI chips versus CPUs means that the United States and its allies need not control CPUs if the goal is to constrain China's use of AI. And the slowing of Moore's Law and general-purpose chip dominance means that CPUs are unlikely to reclaim an important role in AI in the near future. Additionally, such controls could differentiate between AI inference and training chips. AI inference chips are necessary and sufficient for actors who can access trained algorithms. However, AI training chips are necessary for actors who cannot access trained algorithms. As most AI research is open-sourced, many trained algorithms along with their trained neural network weights are published. However, security-relevant AI algorithms developed under government funding would typically not be published.

[96] Limited reporting requirements already exist for U.S. exports to China, Russia, and Venezuela. Expansion of Export, Reexport, and Transfer (in-Country) Controls for Military End Use or Military End Users in the People's Republic of China, Russia, or Venezuela, 85 Fed. Reg. 23,459 (April 28, 2020) (revising 15 C.F.R. § 732, 734, 738, 742, 744, 758, and 774), https://www.federalregister.gov/documents/2020/04/28/2020-07241/expansion-of-export-reexport-and-transfer-in-country-controls-for-military-end-use-or-military-end. However, they do not cover exports from foreign countries. New rules should also require detailed reporting on chip types and volumes and also cover chips packaged in larger computer systems. To minimize regulatory burden, these requirements could be limited to quarterly reports.

[97] A concrete example is if a foreign government is mobilizing a large AI-powered security vulnerability discovery project to perform cyber-operations against the United States and

allies, but is dependent on them for AI chips. The United States could coordinate with its allies on export controls on AI chips to prevent these foreign governments from developing that project while itself investing in AI-powered defensive capabilities. The combinations of these actions could tip the offense-defense balance in favor of the United States. Ben Garfinkel and Allan Dafoe, "How does the offense-defense balance scale?," *Journal of Strategic Studies* 42, no. 6 (2019): 749–753, https://www.tandfonline.com/doi/full/10.1080/01402390.2019.1631810.

[98] U.S.-based Intel also owns leading-edge logic fabs in Ireland and Israel. Controls would need to be crafted to cover these fabs. Additionally, STMicroelectronics has 14 nm logic fabs in France, but focuses on sensors and automotive chips, not AI chips. Cheng Ting-Fang and Laury Li, "Huawei strikes European chip tie-up as fears rise over US curbs," *Nikkei Asia*, April 28, 2020, https://asia.nikkei.com/Spotlight/Huawei-crackdown/Huawei-strikes-European-chip-tie-up-as-fears-rise-over-US-curbs.

[99] The U.K. chip design firm Graphcore has introduced an ASIC, which it calls an IPU and which performs well relative to leading GPUs. Dave Lacey, "Updated Graphcore IPU Benchmarks," *Graphcore*, 2019, https://www.graphcore.ai/posts/new-graphcore-ipu-benchmarks. Microsoft is now using Graphcore chips for its Azure cloud services. Will Knight, "Microsoft Sends a New Kind of AI Processor Into the Cloud," *Wired*, November 13, 2019, https://www.wired.com/story/microsoft-sends-a-new-kind-of-ai-processor-into-the-cloud/. Graphcore's IPU chip is fabricated with TSMC's 16 nm node. Peter Clarke, "Is that Graphcore's Colossus IPU in package?," *eeNews Analog*, October 8, 2018, https://www.eenewsanalog.com/news/graphcores-colossus-ipu-package. The Israeli startup Habana Labs is also introducing AI chips. Frederic Lardinois, "Habana Labs launches its Gaudi AI training processor," *TechCrunch*, June 17, 2019, https://techcrunch.com/2019/06/17/habana-labs-launches-its-gaudi-ai-training-processor/. This chip is also fabricated at TSMC's 16 nm node. James Whanlon, "New chips for machine intelligence," October 4, 2019, https://www.jameswhanlon.com/new-chips-for-machine-intelligence.html. Intel acquired Habana Labs in 2019. Natasha Mascarenhas "Intel's Latest Swing At AI Is A $2 Billion Deal From Israel," *Crunchbase*, December 17, 2019, https://news.crunchbase.com/news/intels-latest-swing-at-ai-is-a-2-billion-deal-from-israel/. Israel also has several other AI chip startups. Uri Berkovitz, "Israel's national AI plan unveiled," *Globes*, November 20, 2019, https://en.globes.co.il/en/article-israels-national-ai-plan-unveiled-1001307979.

[100] This scenario would be especially problematic if Chinese firms can exploit already agreed-to patent licenses to U.S. and U.K. designed IP cores or if China does not enforce patent rights held by foreign AI chip design firms.

[101] Nicholas Bloom, Charles I. Jones, John Van Reenen, and Michael Webb, "Are Ideas Getting Harder to Find?," *American Economic Review* 110, no. 4 (April 2020): 1104–44, https://doi.org/10.1257/aer.20180338.

[102] This program would be similar to SEMATECH, another DARPA program. However, there are some differences. SEMATECH was jointly funded by the public and private sectors. Its public funding was $100 million over six years starting in 1987, and private funding continues to this day. By contrast, the program proposed here does not require firms to provide their own funding and would last a shorter period of time.

[103] EUV photolithography represents a historical example of industry-led pre-competitive R&D. Despite being competitors, leading chipmakers Intel, TSMC, and Samsung together invested in ASML's EUV technology to advance the leading edge of chip fabrication capabilities.

[104] "International Technology Transfer Policies" (Paris: Organisation for Economic Cooperation and Development, January 24, 2019), 31, https://doi.org/10.1787/7103eabf-en. The social returns to even competitive R&D vastly outstrip the returns to the innovator. William D. Nordhaus, "Schumpeterian Profits in the American Economy: Theory and Measurement," NBER Working Paper No. 10433, April 2004, 22, https://www.nber.org/papers/w10433. Semiconductor industry spillovers might be smaller. "Measuring distortions in international markets: The semiconductor value chain" (Paris: Organisation for Economic Cooperation and Development, December 12, 2019), 39, https://doi.org/10.1787/8fe4491d-en. See also Brian Lucking, Nicholas Bloom, and John Van Reenen, "Have R&D Spillovers Changed?," NBER Working Paper No. 24622, May 2018, https://www.nber.org/papers/w24622.

[105] Currently, the United States provides smaller R&D tax incentives than most other OECD countries. John Lester and Jacek Warda, "Enhanced Tax Incentives for R&D Would Make Americans Richer" (Information Technology & Innovation Foundation, September 2020), http://www2.itif.org/2020-enhanced-tax-incentives-rd.pdf.

[106] Current yearly private fab equipment R&D spending is about $9.4 billion a year. For the proposal here to work, SME firms may need to substitute part of that private R&D with the proposed public R&D funding. They may have difficulty simply adding public R&D to existing private R&D, due to difficulties in scaling up R&D activities and because public R&D would eventually expire.

[107] These amounts are only illustrative, as they are sensitive to several assumptions that depend on how export controls are applied and how firms react.

[108] These assets include property, plant, equipment, and long-lived assets. "America's latest salvo against Huawei is aimed at chipmaking in China," *The Economist*, May 23, 2020, https://www.economist.com/business/2020/05/21/americas-latest-salvo-against-huawei-is-aimed-at-chipmaking-in-china.

[109] Bureau of Industry and Security, *U.S. Space Industry "Deep Dive" Assessment*, 15, 28–39.

[110] Stephen Nellis and Alexandra Alper, "U.S.-based chip-tech group moving to Switzerland over trade curb fears," *Reuters*, November 25, 2019, https://www.reuters.com/article/us-usa-china-semiconductors-insight/u-s-based-chip-tech-group-moving-to-switzerland-over-trade-curb-fears-idUSKBN1XZ16L.

[111] "2020 SIA Factbook," Semiconductor Industry Association, 17.

[112] "Sparking Innovation: How Federal Investment in Semiconductor R&D Spurs U.S. Economic Growth and Job Creation" (San Jose, CA: Semiconductor Industry Association, June 2020), 5, https://www.semiconductors.org/wp-content/uploads/2020/06/SIA_Sparking-Innovation2020.pdf.

[113] "Sparking Innovation," Semiconductor Industry Association, 2.

[114] Bob Davis, Asa Fitch and Kate O'Keeffe, "Semiconductor Industry to Lobby for Billions to Boost U.S. Manufacturing," *The Wall Street Journal*, May 31, 2020, https://www.wsj.com/articles/semiconductor-industry-to-lobby-for-billions-to-boost-u-s-manufacturing-11590919201.

[115] CHIPS for America Act, H.R. 7178, 116th Cong. (2020); John Cornyn, "Bipartisan, Bicameral Bill Will Help Bring Production of Semiconductors, Critical to National Security, Back to U.S.," *U.S. Senate*, June 10, 2020, https://www.cornyn.senate.gov/node/5599; James E. Risch, "Risch Introduces Bill to Support Semiconductor Manufacturing in U.S.," *U.S. Senate*, June 26, 2020, https://www.risch.senate.gov/public/index.cfm/2020/6/risch-introduces-bill-to-support-semiconductor-manufacturing-in-u-s.

[116] National Defense Authorization Act for Fiscal Year 2021, S. 4049, 116th Cong. (2020).

[117] SEMI, "World Fab Forecast," November 2020 edition; Varas et al., "Government Incentives," 7.

[118] Fitch et al., "Semiconductor Self-Sufficiency."

[119] Bob Davis, Kate O'Keeffe, and Asa Fitch, "Taiwan Firm to Build Chip Factory in U.S.," *The Wall Street Journal*, May 14, 2020, https://www.wsj.com/articles/taiwan-company-to-build-advanced-semiconductor-factory-in-arizona-11589481659.

[120] Varas et al., "Government Incentives," 1; "Domestic Manufacturing," Semiconductor Industry Association, accessed November 22, 2020, https://www.semiconductors.org/policies/domestic-manufacturing/.

[121] Varas et al., "Restricting Trade with China."

[122] Cecilia Kang and Ana Swanson, "Trump's China Deal Creates Collateral Damage for Tech Firms," *The New York Times*, January 20, 2020,

https://www.nytimes.com/2020/01/20/business/economy/trump-us-china-deal-micron-trade-war.html.

[123] Semiconductor Industry Association, "Proposed Determination of Action Pursuant to Section 301: China's Acts, Policies, and Practices Related to Technology Transfer, Intellectual Property, and Innovation," July 20, 2018, https://www.semiconductors.org/wp-content/uploads/2018/08/Final-_SIA_Submission_on_301_Tariffs.pdf. U.S. chipmakers can easily maintain sufficient ATP functions in the United States at low cost to ensure U.S. government access to secure chips.

[124] Varas et al., "Restricting Trade with China."

[125] 85 Fed. Reg. 51,596.

[126] Robert D. Atkinson, "The Huawei Export Ban: Shooting U.S. Tech Exporters in the Foot," *Information Technology & Innovation Foundation*, January 24, 2020, https://itif.org/publications/2020/01/24/huawei-export-ban-shooting-us-technology-exporters-foot.

[127] President's Council of Advisors on Science and Technology, *Report to the President: Ensuring Long-Term U.S. Leadership in Semiconductors* (Washington, DC: Executive Office of the President, January 2017), 13–14, https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/PCAST/pcast_ensuring_long-term_us_leadership_in_semiconductors.pdf.

[128] "Measuring distortions in international markets: The semiconductor value chain" (Paris: Organisation for Economic Cooperation and Development, December 12, 2019), 84, http://dx.doi.org/10.1787/8fe4491den.

[129] Remco Zwetsloot and Will Hunt, "America's Supply Chain Needs High-Skilled Migrants," *The Wall Street Journal*, May 28, 2020, https://www.wsj.com/articles/americas-supply-chain-needs-high-skilled-migrants-11590706977; John Van Reenen, "Innovation and Human Capital Policy," *The National Bureau of Economic Research*, February 27, 2020, https://www.nber.org/chapters/c14423.

[130] Semiconductor Industry Association, "SIA Workforce Roundtable," March 26, 2018, https://www.semiconductors.org/wp-content/uploads/2018/06/Roundtable_Summary_Report_-_FINAL.pdf.

[131] Will Hunt and Remco Zwetsloot, "The Chipmakers: U.S. Strengths and Priorities for the High-End Semiconductor Workforce" (Washington, DC: Center for Security and Emerging Technology, September 2020), https://cset.georgetown.edu/wp-content/uploads/CSET-The-Chipmakers.pdf.

[132] Hunt et al., "The Chipmakers."

[133] Ellen Proper, "ASML Wins $845 Million Trade-Theft Case Against Bankrupt XTAL," *Bloomberg*, May 4, 2019. https://www.bloomberg.com/news/articles/2019-05-04/asml-wins-845-million-trade-theft-case-against-bankrupt-xtal.

[134] According to one analysis, between 2004 and 2018, around three-fourths of computer hardware/architecture PhDs reported that they planned to stay, with less than ten percent reporting that they plan to leave. In 2018, however, a record number gave no response, possibly due to more restrictions on visas. "The CRA Taulbee Survey," Computing Research Association, 2004–2018, https://cra.org/resources/taulbee-survey/. Additionally, "[a]mong international graduates who earned their doctoral degrees between 2007 and 2009, they found a five-year post-graduation stay rate of 76 percent among engineering graduates and 77 percent among computer science and mathematics graduates. The report also highlighted variation by place of origin: the highest stay rates were found among Chinese and Indian graduates, of whom 86 percent remained in the United States ten years after graduation." Hunt et al., "The Chipmakers."

[135] Khan, "U.S. Semiconductor Exports to China," 19.

[136] The semiconductor and related industries employ about 700,000 workers, of which approximately 220,000 have a graduate technical degree. The North American Industry Classification System (NAICS) coding "334M2: Semiconductor and other electronic component manufacturing, NEC" covers 700,000 workers. The subset of these workers with graduate technical degrees equals 220,000 workers. This latter number approximately represents the high-skill technical workforce that does or could work in the semiconductor industry. Of these, 90,000 were immigrants, with 12,000 from China. (By comparison, 4.4 percent of the full set of 700,000 workers in the "334M2: Semiconductor and other electronic component manufacturing, NEC" are Chinese immigrants.) Roughly half of these Chinese immigrant workers are non-citizens. The subset of the non-citizens that do not hold green cards—for which data is lacking—would be impacted by deemed exports. Hunt et al., "The Chipmakers."

[137] "2020 SIA Factbook," Semiconductor Industry Association, 25. The SIA obtained this estimate by counting semiconductor manufacturing workers listed in the "semiconductor and other electronic component manufacturing" category. However, this category does not include workers in fabless firms. The SIA separately estimated fabless workers who are included in a "wholesale trade" category, then added them to the semiconductor manufacturing worker count to obtain their final estimate. For a previous version of this calculation, see Falan Yinug, "U.S. Semiconductor Industry Employment," January 2015, https://www.semiconductors.org/wp-content/uploads/2018/06/Jobs-Issue-Paper_January_2015-formatted.pdf. Data from the Bureau of Economic Analysis suggests that foreign affiliates of U.S. semiconductor firms employ more workers than their U.S. parents. Bureau of Economic Analysis, *Activities of U.S. Multinational Enterprises, 2017*

(Washington, DC: Department of Commerce, August 23, 2019), 6–7 (Tables 1–2), https://www.bea.gov/system/files/2019-08/omne0819.pdf.

[138] Stephen Ezell and Caleb Foote, "How Stringent Export Controls on Emerging Technologies Would Harm the US Economy" (Information Technology & Innovation Foundation, May 2019), http://www2.itif.org/2019-export-controls.pdf?_ga=2.236208708.476180540.1559330264-658944445.1552315026.

[139] Singapore-based fabless firm Broadcom was blocked from acquiring U.S.-based fabless firm Qualcomm. David McLaughlin, "Trump Blocks Broadcom Takeover of Qualcomm on Security Risks," *Bloomberg*, March 12, 2018, https://www.bloomberg.com/news/articles/2018-03-12/trump-issues-order-to-block-broadcom-s-takeover-of-qualcomm-jeoszwnt. Chinese investment fund Hubei Xinyan was blocked from acquiring U.S.-based SME firm Xcerra. Greg Roumeliotis, "U.S. blocks chip equipment maker Xcerra's sale to Chinese state fund," *Reuters*, February 22, 2018, https://www.reuters.com/article/us-xcerra-m-a-hubeixinyan/u-s-blocks-chip-equipment-maker-xcerras-sale-to-chinese-state-fund-idUSKCN1G703H. Chinese-based Tsinghua Unigroup was blocked from acquiring U.S.-based FPGA-maker Lattice Semiconductor. Seth Fiegerman and Jackie Wattles, "Trump stops China-backed takeover of U.S. chip maker," *CNN*, September 14, 2017, https://money.cnn.com/2017/09/13/technology/business/trump-lattice-china/index.html. China's Fujian Grand Chip Investment Fund was blocked from acquiring Germany-based SME firm Aixtron. Nigel Cory and Robert D. Atkinson, "Why and How to Mount a Strong, Trilateral Response to China's Innovation Mercantilism" (Information Technology & Innovation Foundation, January 13, 2020), https://itif.org/publications/2020/01/13/why-and-how-mount-strong-trilateral-response-chinas-innovation-mercantilism.

[140] "McKinsey on Semiconductors" (McKinsey & Company, 2011), 28–32, https://www.mckinsey.com/~/media/mckinsey/dotcom/client_service/semiconductors/pdfs/mosc_1_revised.ashx.

[141] For more details on national competitiveness in raw materials, see Khan et al., "The Semiconductor Supply Chain." For a list of 35 minerals the Department of the Interior identified as "critical," see Final List of Critical Minerals 2018, 83 Fed. Reg. 23,295 (May 18, 2018), https://www.federalregister.gov/documents/2018/05/18/2018-10667/final-list-of-critical-minerals-2018.

[142] China is also a major supplier of medical supplies including pharmaceuticals to the United States. Yanzhong Huang, "The Coronavirus Outbreak Could Disrupt the U.S. Drug Supply," *Council on Foreign Relations*, March 5, 2020, https://www.cfr.org/in-brief/coronavirus-disrupt-us-drug-supply-shortages-fda; Ana Swanson, "Coronavirus Spurs U.S. Efforts to End China's Chokehold on Drugs," *The New York Times*, March 11, 2020, https://www.nytimes.com/2020/03/11/business/economy/coronavirus-china-trump-drugs.html. However, pharmaceutical supply chains are not well understood, and by many

measures, the majority of U.S. consumption comes from domestic production or imports from countries other than China. Eric Boehm, "Why You Shouldn't Trust Anyone Who Claims 80 Percent of America's Drugs Come From China," *Reason*, April 6, 2020, https://reason.com/2020/04/06/why-you-shouldnt-trust-anyone-who-claims-80-percent-of-americas-drugs-come-from-china/.

[143] For details on expanding U.S. semiconductor export controls since 2019, see Khan, "U.S. Semiconductor Exports to China."

[144] "China's export control laws to be used to break US 'long-arm' jurisdiction: analyst," *Global Times*, October 18, 2020, https://www.globaltimes.cn/content/1203798.shtml.

[145] In 2010, China applied export controls to Japan for rare earths. These controls backfired for China, as Japan helped invest in Australian-based Lynas Corporation, which developed operations in Australia and Malaysia and is now the second largest provider of rare earths. David Fickling, "We All Need to Calm Down About Rare Earths," *Bloomberg*, May 30, 2019, https://www.bloomberg.com/opinion/articles/2019-05-30/we-all-need-to-calm-down-about-rare-earths. Other countries have also increased production. United States Geological Survey, *Mineral Commodity Summaries 2020*, 132–133.

[146] The United States has reserves equivalent to nearly seven years of global production (at the 2019 rate of production), while all non-Chinese countries have reserves equivalent to over three centuries of global production. United States Geological Survey, *Mineral Commodity Summaries 2020*, 132–133.

[147] U.S.-China Economic and Security Review Commission, "Hearing On Technology, Trade, and Military-Civil Fusion: China's Pursuit of Artificial Intelligence, New Materials, and New Energy," June 7, 2019, 168, https://www.uscc.gov/sites/default/files/2019-10/June%207,%202019%20Hearing%20Transcript.pdf.

[148] Shannon Davis, "Rare Earth Elements Supply Uncertain for IC Fabs," *Semiconductor Digest*, July 29, 2020, https://www.semiconductor-digest.com/2020/07/29/rare-earth-elements-supply-uncertain-for-ic-fabs/.

[149] For several policy recommendations, see James Mattis, James O. Ellis Jr., Joe Felter, and Kori Shake, "Ending China's chokehold on rare-earth minerals," *Bloomberg*, September 18, 2020, https://www.bloomberg.com/opinion/articles/2020-09-18/ending-china-s-chokehold-on-rare-earth-minerals.

[150] However, it is possible that some of the non-Chinese-origin U.S. imports are for high-grade gallium by producers who themselves imported low-grade gallium from China.

[151] United States Geological Survey, *Mineral Commodity Summaries 2020* (Reston VA: Department of the Interior, 2020), 62–63, https://pubs.usgs.gov/periodicals/mcs2020/mcs2020.pdf. A 2013 analysis concluded

that there were medium-high risks of supply chain restrictions to gallium and indium, with low-medium and medium-high potential impacts to the United States. John Adams, "Remaking American Security: Supply Chain Vulnerabilities & National Security Risks Across the U.S. Defense Industrial Base" (Alliance for American Manufacturing, May 2013), 53, https://docs.house.gov/meetings/FA/FA14/20130725/101216/HHRG-113-FA14-Wstate-AdamsB-20130725.pdf.

[152] A 2015 estimate suggested a minimum supply potential of 2,775 tons in 2015. Max Frenzel, Marina P. Ketris, Thomas Seifert, and Jens Gutzmer, "On the current and future availability of gallium," *Resources Policy* 47 (March 2016): 38–50, https://www.sciencedirect.com/science/article/abs/pii/S0301420715001233. By comparison, 2019 production was 720 tons. United States Geological Survey, *Mineral Commodity Summaries 2020*, 62–63.

[153] "Low gallium demand balances production cuts," *Argus Media*, July 16, 2019, https://www.argusmedia.com/en/news/1940477-low-gallium-demand-balances-production-cuts.

[154] "Xi Jinping is trying to remake the Chinese economy," *The Economist*, August 15, 2020, https://www.economist.com/briefing/2020/08/15/xi-jinping-is-trying-to-remake-the-chinese-economy.

[155] Hunt et al., "China's Progress in Semiconductor Manufacturing Equipment."

[156] Lester Ross, Kenneth Zhou, Tingting Liu, "China's New Export Control Law," *WilmerHale*, October 21, 2020, https://www.wilmerhale.com/en/insights/client-alerts/20201021-chinas-new-export-control-law.

[157] "China's first entity list may target foreign entities blocking Chinese firms' supplies: experts," *Global Times*, September 19, 2020, https://www.globaltimes.cn/content/1201374.shtml.

[158] "China to slap countermeasures on unjustified extraterritorial application of foreign laws amid US bullying sanctions," *The Global Times*, January 9, 2021, https://www.globaltimes.cn/page/202101/1212274.shtml.

[159] Cheng Leng, Keith Zhai, and David Kirton, "Exclusive: China preparing an antitrust investigation into Google – sources," September 30, 2020, https://www.reuters.com/article/us-google-china-huawei-tech-exclusive-idUSKBN26L1OH.

[160] Ian King, Evelyn Yu, Steven Yang, and Yuan Gao, "Huawei, China Firms Are Said to Seek Curbs on Nvidia's Arm Deal," *Bloomberg*, October 20, 2020,

https://www.bloomberg.com/news/articles/2020-10-21/huawei-china-firms-are-said-to-seek-curbs-on-nvidia-s-arm-deal.

[161] Alan Patterson, "Electronics Supply Chains Splitting Between China and U.S.," *EETimes*, August 19, 2020, https://www.eetimes.com/electronics-supply-chains-splitting-between-china-and-u-s/.

[162] United States Geological Survey, *Mineral Commodity Summaries 2020*.

[163] Although the United States has relatively low import reliance on China for tungsten, China does produce virtually all of a processed form of tungsten called ammonium paratungstate.

U.S.-China Economic and Security Review Commission, "Hearing On Technology, Trade, and Military-Civil Fusion," 168.

[164] Khan, "U.S. Semiconductor Exports to China."

[165] Khan et al., "The Semiconductor Supply Chain." Robert Castellano, "Semiconductor Equipment Revenues To Drop 17% In 2019 On 29% Capex Spend Cuts", *Seeking Alpha*, March 27, 2019, https://seekingalpha.com/article/4251198-semiconductor-equipment-revenues-drop-17-percent-2019-29-percent-capex-spend-cuts.

[166] "World Fab Forecast," SEMI, November 2020 edition.

[167] These percentages are based on CSET analysis of shareholder reports, which provide country revenue for the firms as a whole.

[168] SEMI, "World Fab Forecast," November 2020 edition.

[169] 2021 fab equipment spending projections from SEMI, "World Fab Forecast," November 2020 edition. Country market shares from VLSI Research. Gross margins from company financial statements.

[170] Global chip demand, including from China, is independent of where chips are manufactured. Therefore, the United States and allied democracies would gain local manufacturing capacity proportionate to whatever degree China loses or fails to develop that capacity (ignoring the effect of Chinese subsidies). However, there could be some lag before new non-Chinese fabs fulfill lost SME demand from China. A leading-edge greenfield fab takes about three years to build. A "greenfield" fab is a new rather than upgraded fab. An upgrade bringing new SME online requires 12 to 15 months. Fuller, "Cutting Off Our Nose." However, three deductions are applied to this value. First, CSET analysis of several SME firms shows shipment backlogs of close to 50 percent of yearly revenue at a given time, with a median fulfillment time of about six months. Combining these numbers, about three months of SME revenue is typically delayed. Second, we assume firms have three months of notice before export controls are implemented. Within this time period, non-Chinese fabs

could plan new fabs in response to expected changes in market conditions. Third, we assume SME firms start shipping fab equipment to fabs six months before construction completion, meaning SME firms would not be deprived of revenue during this time. Applying these three deductions to fab construction time produces a final value of two years.