Policy Brief

Through a Glass, Darkly: Mapping Emerging Technologies and Their Supply Chains

Using CSET's Map of Science and Supply Chain Explorer

Author
John VerWey

CSET CENTER *for* SECURITY *and* EMERGING TECHNOLOGY

August 2023

Executive Summary

Emerging technologies are of keen interest to policymakers, private firms, and researchers because of their perceived economic and national security promise. Private firms and researchers hope to invent and commercialize the next ubiquitous technology. Governments want to understand what policies they can pursue to increase domestic innovation in these technologies and, in some circumstances, deny adversaries access to these technologies. At the same time this interest in emerging technologies has spiked, ongoing supply chain interruptions have exposed the worldwide reliance and fragility of some technologies' global value chains.

This confluence of factors has highlighted shared challenges and opportunities: emerging technologies and supply chains are largely developed and controlled by private-sector firms. However, information about both can be revealed through careful analysis of public information. This information can inform policymakers' efforts to increase competitiveness in both emerging technologies and their supply chains. This paper argues that policymakers' efforts to increase competitiveness in emerging technologies and resilience in supply chains should be closely coordinated and aligned.

Efforts to identify emerging technologies and associated supply chains are challenged by the fundamental nature of emerging technologies. By definition, emerging technologies are new and rapidly changing, making them hard to track. Because these technologies are inherently immature, the underlying supply chain of people, processes, products, services, information, and resources that supports the technology is difficult to define. Additionally, technology development is diffuse and occurs in universities, firms, and government labs, often simultaneously and across borders.

Academia, industry, and government have attempted to identify emerging technologies for decades. Each of the analytical approaches used by academia, industry, and government comes with trade-offs. This work is inherently speculative and predictive. There is no agreed-upon methodology for identifying emerging technology.

In contrast, the concept of supply chain security is much more mature. Industry maintains a wide variety of supply chain risk management practices designed to increase resilience, there is an active field of academic research focused on mapping global value chains, and governments have experience managing supply chains, particularly those relevant to national security.

Efforts to identify emerging technologies and increase supply chain security both require, and profit from, the same analytic base. This paper first assesses the challenges of promoting emerging technologies and the tools that may assist in this. It then turns to supply chains and shows how the similar sources of information and analytical methods can increase resilience. This paper concludes with a template policymakers could use to map emerging technology supply chains based on two tools developed by CSET's Emerging Technology Observatory (ETO): the Map of Science and the Supply Chain Explorer.

Table of Contents

Introduction

Governments around the world are engaged in policymaking to protect and promote emerging technologies.[*] In particular, governments in Europe, the United States, and Asia are all pursuing policies and regulations designed to cultivate emerging technology innovation at a pace that exceeds competitors ("promote") and deny perceived competitors access to these technologies ("protect").[1] A similar paradigm exists with respect to supply chains, with policymakers focused on increasing domestic supply chain resilience to minimize future disruptions ("promote") while also leveraging supply chain choke points under their control to slow perceived competitors' ascendence ("protect").

This paper asserts that policymakers' efforts to protect and promote emerging technologies and supply chains should be inextricably linked. The former is much more speculative and necessarily predictive, while the latter is much more concrete and urgent. However, the underlying analytic effort draws on the same sources of information and methodological approach. Efforts to protect and promote emerging technologies will be made stronger by borrowing sources and methods from the supply chain security world, and vice versa.

The current focus on emerging technologies is largely due to the shared perception that looming advances in key areas such as biotechnology, artificial intelligence/machine learning (AI/ML), quantum computing, and advanced classical computing will confer asymmetric economic and national security advantages in the coming decades. For example, the first country to successfully develop a quantum computer that exceeds the capabilities of classical computers would theoretically be able to achieve singular advances in drug discovery, weather forecasting, encryption-breaking, and other computationally intensive tasks.[†] However, from a supply chain perspective, efforts to protect and promote quantum computing are only as good as

---

[*] The concepts of "emerging technology," "converging technology," and "disruptive technology" are all distinct, but interrelated. For the purposes of this paper, an emerging technology is "a relatively fast growing and radically novel technology characterized by a certain degree of coherence persisting over time and with the potential to exert a considerable impact on socio-economic domain(s)." Daniele Rotolo, Diana Hicks, and Ben R. Martin, "What Is an Emerging Technology?" arXiv:1503.00673v4 (2015), https://arxiv.org/abs/1503.00673. Appendix 2 contains additional context.

[†] While it is a common assumption that the "first mover" on an emerging technology gains asymmetric advantages, it is an open question whether this is actually true or whether any such advantage obtained is significant.

efforts to protect and promote the underlying supply of dilution refrigerators, high-density ribbon cables, and specialty wiring that enable quantum processors.[2]

There is an overwhelming amount of information on emerging technologies today. By one count, there were at least 78 lists of emerging technologies published by government, industry, academia, journalists, and nonprofits in recent years.[3] However, general lists that identify “artificial intelligence” as an emerging technology are of limited utility for policymakers.[4] A more rigorous and granular approach is necessary to identify and map these technologies to characterize how one country’s industry is doing relative to another and what policies might protect and promote innovation. Policymakers must understand which entities (from individuals to firms) lead; the scope, scale, and pace of their efforts; and what market opportunities and failures exist. Leveraging sources and methods traditionally employed in service of supply chain security can empower policymakers to take a more rigorous and granular approach.

Policymakers face several challenges in their efforts to map emerging technologies and their supply chains.

- **Definitional uncertainty**: There is no agreed-upon set of criteria used to identify a technology as “emerging.”
- **Pace of progress**: By definition, emerging technologies change quickly. Frequently, the speed with which an emerging technology develops exceeds policymakers’ ability to characterize and analyze the technology.
- **Incomplete or proprietary data**: Most emerging technology innovation occurs in the private sector. Absent the ability to directly evaluate progress being made on a particular technology, policymakers need access to high-fidelity information sources that can serve as a proxy to identify a particular technology’s potential emergence and its underlying supply chain. This information is frequently overwhelming, disorganized, and has a short half-life as the technology continues to emerge.

These specific challenges are compounded by emerging technology’s general unpredictability. Even in instances where a technology is well defined, its pace of progress is characterized, and associated information is known, it is difficult to judge which policy interventions will most productively protect and promote emerging technologies. The literature on prediction suggests that human desire for prediction will always exceed human ability to predict.[5] This is especially true in the context of national security challenges and emerging technology, where governments must make investments in technologies to address perceived future threats. All of these challenges are magnified by the increasing desire to conduct comparative assessments of U.S. technology capabilities and trajectories relative to developments in other countries.

These challenges are not abstract. The U.S. government regularly solicits public comment and expertise to inform policymaking, particularly on efforts aimed at protecting and promoting emerging technologies as well as supply chains. A review of 20 such solicitations for public comment (See Table 1 and Appendix 1) from 2018–present indicates that policymakers are asking the same questions about emerging technologies and supply chains: how U.S. competitiveness compares to other countries', what observable risks exist, what policymakers can do to address these risks and increase U.S. competitiveness domestically, and how the United States can work internationally to establish and maintain leadership in emerging technologies and build resilient supply chains. Whether policymakers are considering the imposition of new export controls on brain computer interfaces, how best to increase U.S. research and development in artificial intelligence, or characterizing risks in semiconductor supply chains for defense systems, the information they seek is generally publicly available, but it is frequently technical, proprietary, poorly organized, and unconsolidated.

Table 1. Key Subjects of Recent U.S. Government Requests for Information (RFIs) on Supply Chains and Emerging Technologies

Subject	Supply Chain Context	Emerging Technology Context
Technology Definition	Which technology supply chains are "critical"	How to identify "emerging" technologies
Technology Mapping	What domestic sectoral capabilities exist; what capabilities exist overseas	Which academics, companies, and countries are engaged in R&D of a particular technology
Competitiveness	Whether domestic production can meet domestic demand and, if not, what is net import reliance	How does U.S. research quality compare with the rest of the world (e.g., citation intensity)
Technology Ecosystem	How does the U.S. supply chain compare with/integrate with the worldwide supply chain	What enabling technologies support emerging technology R&D, and from whom are they sourced
Technology Pace of Progress	How mature and/or substitutable is the technology, what is the Technology Readiness Level (TRL)	What is the pace of progress, path to commercialization, and timeline
Technology Leadership	Who are the leading suppliers of a particular technology, what alternatives exist	Where is the best/most advanced research being conducted and by whom
Workforce	Is the domestic workforce sufficient (e.g., scale, skills) to meet domestic production requirements	Where are leading researchers employed and located
International Collaboration	Can supply be diversified through an increase in allied production	What are the primary avenues for collaboration between researchers
Risks	Do any choke points (e.g., single, sole-source suppliers) exist in terms of technology or companies; what vulnerabilities exist	Are there roadblocks (e.g., regulatory, technical) that will affect the pace of innovation; does a technology present national security risk
Government Options	What can policymakers do to increase supply chain resilience	What can policymakers do to protect and promote a given technology's development

Source: Author's compilation, derived from sources cited in Appendix 1.

This paper addresses each of the aforementioned challenges sequentially. First, it reviews past and current efforts to identify emerging technologies to date. Second, it provides background on public and private-sector supply chain security and risk management efforts. Third, it reviews CSET's Map of Science and Supply Chain Explorer, two recently introduced tools that policymakers can use to identify emerging technologies and map them. It reviews how these tools integrate best practices used for identifying emerging technologies and mapping supply chains, respectively, serving as a starting point for policymakers interesting in mapping emerging technology supply chains.

Background: Why Emerging Technologies and Supply Chains?

Economic Competitiveness

The economic promise of emerging technologies is well understood by policymakers who have observed the rise of leading hardware and software technology companies in the preceding decades. Germany's "hidden champions,"[6] China's "Big 4" tech giants (Baidu, Alibaba, Tencent, and Xiaomi), and the United States' "Big 5" tech giants (Alphabet [Google], Amazon, Apple, Meta [Facebook], and Microsoft) all enjoy large market shares. These leading positions protect them from competition and provide them with profit margins sufficient to fund internal R&D efforts to perpetuate their leading positions. For example, Google's 90 percent search engine market share fuels its 25 percent market share in U.S. digital ad sales, the profits from which are used to fund moon-shot projects, such as its Quantum Artificial Intelligence initiative.[7] Policymakers assume private firms that establish meaningful leads in today's emerging technologies will enjoy similar competitive positions in the coming decades because of their first-mover advantages.[*] As a result, policymakers are undertaking efforts aimed at identifying and promoting innovation in emerging technologies to ensure the next tech giants are housed in their respective countries.

---

[*] Note, however, that there is a body of research that disagrees with this assumption. A survey of 65 million publications, patents, and software products from 1954–2014 demonstrated that, across this period of time, smaller teams tend to *disrupt* science and technology with new ideas and opportunities, whereas larger teams tend to *develop* existing ones. This suggests major incumbents struggle to develop emerging or disruptive technologies. Lingfei Wu, Dashun Wang, and James A. Evans, "Large teams develop and small teams disrupt science and technology," *Nature* 566, (2019): 378–382, https://www.nature.com/articles/s41586-019-0941-9.

National Security

The national security promise of emerging technologies is similarly well understood by policymakers. Countries attempt to fund and cultivate domestic technology capabilities that confer comparative military advantages, while pursuing policies to mitigate any perceived technology advantages enjoyed by competitors' militaries. During the Cold War, U.S. investments in the nuclear navy, precision navigation, stealth aircraft, and intercontinental ballistic missile technology were all motivated by defense priorities and, for a time, conferred asymmetric military advantage. Over time, some of these technologies have become commercialized and today's commercial nuclear power sector, global positioning systems, carbon fiber composite manufacturers, and orbital rocket launch industry all owe some of their success to earlier government-funded investments that pushed associated technologies toward emergence.

Emerging Technology Competition and the Private Sector

Importantly, all of the aforementioned defense technologies were invented and commercialized using extensive government-directed funding and, in many cases, came about because of innovation occurring in government labs. Historically, this gave governments good visibility into the pace of progress in specific emerging technologies and provided policymakers with options to cultivate and control the supply chain of a given technology. The majority of emerging technology innovation today is occurring in the private sector, where firms are developing and commercializing technologies that have clear economic promise, but may also confer military advantage. For example, advanced battery technology being developed by an automotive firm for use in electric vehicles may result in breakthroughs in energy density ratios for batteries more generally, which could have important performance benefits for aerial and underwater autonomous vehicles fielded by the military.[*] These so-called "dual-use" technologies present a particular challenge for policymakers, who must carefully interpret public and private information to identify and evaluate which technologies hold economic and national security promise worthy of protection and promotion.

Notably, both the United States and China have passed new export control laws in the past five years to restrict the transfer of particular software, equipment, and knowledge essential for emerging technology development.[8] The United States' 2018

---

[*] These potential breakthroughs could also benefit soldiers who today carry a significant weight of batteries into combat. This weight is compounded because batteries for different systems are incompatible, so they have to carry spare batteries for every device.

Export Control Reform Act mandated that the U.S. Department of Commerce's Bureau of Industry and Security (BIS)—the U.S. government's lead agency tasked with protecting dual-use technologies—begin a process of identifying so-called "emerging"[9] and "foundational"[10] technologies for new controls.[11] In response, BIS placed new controls on 38 technologies from 2018 to 2022 before walking back its attempts to identify technologies as "emerging" or "foundational" in May 2022 because of difficulties defining, and distinguishing between, the two.[12]

Simultaneously, both the United States and China have passed laws allocating billions in support to specific emerging technology industries to promote innovation and "win the race by running faster." These efforts have focused on (1) identifying particular technologies as "critical" or "emerging,"[*] (2) assessing competitiveness in these technologies relative to peers and competitors, and (3) determining what policies could increase and accelerate innovation. For example, the United States recently passed the CHIPS and Science Act, allocating $52 billion to increase semiconductor manufacturing capacity in the United States, while China is reportedly contemplating a $143 billion response focused on increasing its own domestic chip production capacity.[13] This focus, however, invites the question of which particular semiconductor technologies are important for policymakers interested in promoting (and protecting) this contested industry. Answering this question requires that policymakers develop a holistic understanding of the worldwide semiconductor supply chain, as well as a more general framework for evaluating emerging technology supply chains. Because nearly all emerging technology development is happening in the private sector, governments must carefully interpret open-source information to assess relative strengths and weaknesses.

[*] See, for example, China's Made in 2025 list and the U.S. Critical and Emerging Technologies List.

Identifying Emerging Technologies

Identifying Emerging Technologies: Sources of Information

There is a wide variety of publicly available and commercially available information that provides insight into emerging technology innovation and progress (Table 2). This presents challenges and opportunities for policymakers. To be sure, nearly all emerging technology development is happening in the private sector, so a great deal of information is not shared publicly. For example, Google's X division (colloquially known as its "moon-shot factory") places a wide variety of high-risk, high-reward bets on technologies, but public knowledge of these technologies and their underlying supply chain is limited to what Google chooses to divulge.

However, firms also face commercial incentives to publicize and protect their innovation, especially through journal articles, patent filings, standards-setting organizations, and conferences. Careful scrutiny of these data sources can reveal information about the nature and pace of a technology's development, which researchers lead the field, and what firms assess to be the next high-risk, high-reward technology.

Table 2. Select Sources of Information Relevant to Emerging Technology Assessments

Type of Data	Example Resources
Patent Filings	USPTO; Google Patents; PatSnap; Dimensions Digital Science; Lens
Journal Articles	SSRN; Semantic Scholar; arXiv; CiteSpace; VOSviewer; Clarivate Web of Science; the Chinese National Knowledge Infrastructure (CNKI); Dimensions Digital Science; Scopus; OpenAlex; Lens
Investment Data (Mergers, Acquisitions, Joint Ventures, Funding Rounds)	Crunchbase; Pitchbook; CB Insights; Refinitiv
Public Research and Development Expenditures	USASpending; Fraunhofer Society; National Science Foundation; Dimensions Digital Science
Technical Standards-Setting Organizations	ISO; JEDEC; 3GPP; O-RAN Alliance; 5GAA
Medicine, Chemistry	MeSH; PubMed; SciFinder
Software Development	GitHub; AIminer; Papers with Code
Conference Proceedings and Conventions	HotChips; SC; IEEE; SRC; ACM

Source: Author's compilation.

The sources of information described in Table 2 have trade-offs. Some resources are limited by language (e.g., they are only available in English), scope (e.g., they cover a narrow topic), technical depth (e.g., they are not intelligible to lay users), cost (e.g., they are paywalled), time series (e.g., they cover a limited period of time and/or are not frequently updated), reliability (e.g., they are crowdsourced or unvetted), or terms and conditions that restrict their use. Conversely, some resources are open to the public, free, easily navigated, and allow users to filter by desired characteristics, but they do not offer downloadable metadata or lack user-friendly interfaces. There is no one resource that provides worldwide coverage of high-fidelity data on emerging technology development.

However, by combining and interpreting information from different sources (i.e., comparing patent filings, academic publications, and public R&D funding for a specific technology), it is possible to characterize an emerging technology's development. For example, a technology that displays intensive patent filings and publications relative to a decade ago is exhibiting growth that may make it "emerging." Conversely, a technology that lacks a community of interest and has no record of affiliated venture capital investments may be either too ahead of, or behind, its time to be considered "emerging."

Identifying Emerging Technologies: Methods

There is an overwhelming amount of relevant, but disorganized, information available to spot "signals" of emerging technology, and various methodological approaches are used. Efforts to identify technology emergence have occurred for decades. These efforts cross disciplines and include the philosophy of science,[14] progress studies,[15] foresight,[16] infometrics,[17] scientometrics,[18] bibliometrics,[19] and network science,[20] among others. A 2015 survey of attempts to identify emerging technologies identified five attributes in academic literature characteristic of emerging technologies: (1) radical novelty, (2) relatively fast growth, (3) coherence, (4) prominent impact, and (5) uncertainty or ambiguity (see Appendix 2 for greater detail and examples of each characteristic).[21] Policymakers interested in identifying emerging technologies can use the aforementioned sources of information to filter for these signals, and tools have been developed to that end, but a scalable solution is required.

The volume and complexity of information on worldwide science and technology development necessitates tools for aggregation and analysis. The National Science Foundation estimates there were 2.9 million academic articles published in 2020.[22] That same year, the U.S. Patent and Trademark Office received 646,000 patent applications.[23] Many search engines and tools allow users to explore relevant information such as publications (e.g., arXiv), government funding (e.g., USAspending), investment (e.g., Pitchbook), and patent filings (e.g., Google Patents) to assess a particular technology. However, these stand-alone services lack essential qualitative context and are not scalable for policymakers interested in interpreting trends across technical fields worldwide. For example, no resource exists where policymakers can simultaneously compare worldwide public and private-sector funding of research on sodium-ion batteries as well as associated patent and publication activity. And, even if such a resource existed, policymakers might not have access to the subject matter expertise needed to make sense of arcane technical areas of emerging research or of the underlying supply chain that supports the battery ecosystem writ large.

Academic Methods

Academic efforts to identify emerging technologies attempt to aggregate progress across fields of study to inform future research priorities. Experts have tried to create maps of scientific domains to identify emerging technologies for over 50 years.[24] A recent survey of scientometric and bibliometric visualization and analysis software identified 16 current programs used to extract, process, and visualize data on science based on publication and citation metrics.[25] In general, these tools function by ingesting large volumes of information from separate academic journals, preprocessing that data (de-duplicating, text segmentation), cross referencing the data (also referred to as "normalization"), clustering (grouping together datapoints by topic or subtopic), and providing some network visualization function to demonstrate relationships between subject areas, time series, citation intensity, and other proxies for innovation or emergence.[26] There are likely dozens of additional software platforms that offer similar functionality,[*] including CSET's Map of Science (discussed below), as well as more generic services that offer text mining and visualization that could be applied to emerging technologies. However, they all come with trade-offs. These tools vary widely in terms of scope, relevance, and access. For example, some of the free open-access platforms are focused on a specific academic discipline, lack the ability to integrate non-English publications, or irregularly ingest updated publications.

Industry Methods

The private sector engages in efforts to identify emerging technologies to assess opportunity and risk. Private-sector "horizon scanning" and "foresight" efforts are

---

[*] For example, a separately cultivated list includes an additional roughly 10 services: Hamid R. Jamali, "Scientometric Portal," https://sites.google.com/site/hjamali/scientometric-portal.

distinct from academic methods in their focus on identifying commercial opportunity.[27] Firms such as Boeing and Intel have business intelligence arms specifically designed to identify and invest in the next generation of aviation and semiconductor technologies, respectively, to protect their leading positions. Large multinational corporations also maintain market intelligence units tasked with managing their existing supply chains, evaluating patent filings, and understanding how their company's products compare with competitors. Similarly, the venture capital industry makes investments in start-ups based on evaluations of their potential for growth, market share, and perceived demand signals. Venture capitalists also closely monitor worldwide investment trends to identify technologies that are seeing growing levels of investment.[28]

Private-sector methods to identify emerging technologies are narrowly tailored and prioritize commercial opportunity over strategic value. In practice, these efforts attempt to identify "low-risk" emerging technologies that promise quick returns and/or solve a discrete problem. A recent study observed that, because venture capital investors usually solicit funds for a 10-year period, they are incentivized to invest in software and services start-ups and away from start-ups engaged in hardware, materials science, and technology that is perceived to be "less nimble."[29] Relatedly, corporate research and development arms engaged in technology development focus their funds on applied R&D for narrow use cases, as opposed to capital-intensive basic R&D.[30] Firms assess the opportunity and risk of a particular technology with respect to their business and lack incentives to invest R&D budget in a technology for which they do not perceive commercial promise.

Government Methods

Governments undertake efforts to identify emerging technologies "to avoid [science and technology] surprise, to inflict surprise on adversaries, and to leverage advances for the benefit of the nation."[31] These efforts inform policymakers' prioritization of research and development investment and divestment, expert identification and collaboration, military advantage, and technology transfer. The U.S. government has previously established entities tasked with monitoring and evaluating technology, such as the Office of Technology Assessments. While this office was disbanded in 1995, other governments maintain offices with similar functions, such as Germany's TAB, the United Kingdom's Parliamentary Office of Science and Technology, the Swiss Foundation for Technology Assessment, and the European Commission's Joint Research Centre (JRC).[32]

Weak Signals in Science and Technologies in 2021[33]

"Early identification of today's emerging technologies is key for the design of new policies by policymakers, who need to be made aware of potentially disrupting technologies or scientific development as early as possible to develop well-fitted policies that secure both a stable business environment for industrial actors and a safe and secure society for citizens to live in."

- Joint Research Centre, European Commission

One model that U.S. policymakers could choose to emulate is the European Commission's JRC, which is tasked with technology monitoring and assessment on behalf of European policymakers. As part of this function, the JRC introduced a new iteration of a web-based platform in 2019 called the Tools for Innovation Monitoring (TIM) system. Simultaneously, the JRC released the first of a now-annual series of reports called "Weak signals in science and technologies."[34] The JRC has also created custom instances of this tool focused on specific subjects, including energy, cybersecurity, dual-use technologies, and emerging technologies.[35] These instances allow users to filter information in a variety of other manners, visualizing how technology competitiveness compares between countries and research institutions. The JRC has also conducted related research on specific supply chains.[36]

Current U.S. government efforts to identify emerging technologies are decentralized and spread across various agencies. Notably, the Department of Homeland Security maintains a science and technology horizon-scanning team,[37] the Department of Defense has a science and technology futures office as well as the Defense Advanced Research Projects Agency (DARPA),[38] and the Government Accountability Office has a Science and Technology Assessment division.[39] This is an indicative, not exhaustive, list of current U.S. government efforts and reflects the fragmented approach the U.S. government has taken to date. These entities are generally designed to evaluate technologies with reference to their specific departmental taskings, not on behalf of the whole U.S. government.

In addition to technology evaluation to avoid strategic surprise, U.S. government efforts to identify emerging technologies are meant to help prioritize federal research and development funds. Thirteen U.S. government agencies distribute $24.9 billion (as of FY21) to 42 Federally Funded Research and Development Centers (FFRDCs) engaged in basic and applied science and technology research.[40] A separate system of

Department of Defense University Affiliated Research Centers (UARCs) provide engineering, research, and development capabilities for the military.[41] The National Science Foundation tracks research in the United States and worldwide to determine which research topics, and researchers, to fund. In practice, the NSF maintains grants and cooperative agreements with more than two thousand education institutions and receives over 42,000 proposals per year to fund advances in science and technology.[42] Trends in science and technology are reviewed in the context of funding decisions to prioritize the basic and applied research undertaken by these FFRDCs, UARCs, and NSF grantees.[*]

The most recent systematic attempt by the U.S. government to identify emerging technologies was undertaken by the Intelligence Advanced Research Projects Activity (IARPA). Beginning in 2010, IARPA funded a program called Foresight and Understanding from Scientific Exposition (FUSE) to "develop automated methods that aid in the systematic, continuous, and comprehensive assessment of technical emergence using publicly available information found in published scientific, technical and patent literature."[43] A related IARPA program, Forecasting Science & Technology (ForeST), built on FUSE to "develop and test methods for generating accurate forecasts for significant science and technology (S&T) milestones."[44]

However, U.S. government efforts to date do not systematically leverage and integrate the scale of open-source science and technology information available today to identify emerging technologies to inform policymakers. While this challenge has been observed for decades, it has recently gained new urgency given the importance of protecting and promoting the science and technology ecosystem in the context of strategic competition.[45] In response to a perceived need for greater centralization and persistent technology scanning, proposals to create a National Techno-Economic Intelligence Center, a Center for Global Competition Analysis, and/or a Technology Competitiveness Council are currently under consideration.[46]

Mapping Supply Chains

Every supply chain is complex in its own way.[47] This presents a challenge for policymakers interested in mapping a particular technology's supply chain. For example, the supply chain for nonphysical services such as artificial intelligence algorithms loosely consist of data, software, hardware, and workforce.[48] Conversely, the supply chains for a physical product such as an electric vehicle battery loosely

[*] Note: the scale and breadth of federal research and development funding efforts is far greater than the indicative examples described here.

consist of raw materials, processed materials, subcomponents, manufacturing, and recycling.[49]

Policymakers engaged in efforts to protect and promote emerging technologies are asking questions and soliciting answers that have traditionally been the purview of supply chain analysis. Until recently, private-sector supply chain analysis was the remit of procurement experts, private-sector risk managers, and academics who were concerned with understanding international commerce through the lens of how products and services get delivered on time, to specification, and at the quoted cost. Government interest in supply chains shared these priorities, with an added emphasis on minimizing the possibility that corrupt or counterfeit components ended up in national security systems. This is changing, however, as policymakers have begun to ask questions related to techno-economic competition following the widely publicized recent supply chain disruptions. Policymakers interested in understanding how a product or service is made, who leading domestic and international vendors are, where they are located, what alternatives exist, and the delta between domestic production and consumption are asking questions that supply chain analysis is empowered to answer.

The uniqueness of each supply chain complicates efforts to develop a technology mapping template and, frequently, supply chains overlap or become cyclical. For example, while the commercial aviation, semiconductor, and AI supply chains are all distinct, each of them connects to one another. The AI supply chain relies on the semiconductor supply chain for hardware, while the semiconductor supply chain relies on the commercial aviation industry for transportation logistics.[50] Relatedly, AI algorithms increasingly accelerate semiconductor design times, while semiconductors form the foundational components for all electrical components in aircraft and their avionics systems.[51]

Mapping Supply Chains: Sources of Information[*]

Technology supply chains are often entirely commercial and outside government control. Additionally, limited data is available at the multiple tiers of vendors located in countries around the world, making this effort more complex. "Tiers" refer to different levels in a supply chain. Supply chain tiers are easily understood by thinking about

[*] This section is partially derived from: John VerWey, "U.S.-China Competition in Global Supply Chains," U.S.-China Economic and Security Review Commission, June 2022, https://www.uscc.gov/sites/default/files/2022-06/John_VerWey_Testimony.pdf.

aircraft manufacturing. A plane is provided by an original equipment manufacturer. This OEM relies on Tier 1 vendors to provide various components such as wings, engines, avionics, and tires. Tier 1 vendors rely on Tier 2 vendors to supply subcomponents. For example, avionics suppliers rely on electronic assemblies. These Tier 2 suppliers rely on Tier 3 suppliers for items that go into electronic assemblies, such as printed circuit boards and integrated circuits. And these Tier 3 suppliers rely on Tier 4 suppliers for equipment used to fabricate PCBs and ICs. Finally, Tier 4 suppliers rely on Tier 5 suppliers for raw materials, such as silicon. Mapping supply chains gets progressively more difficult the "deeper" one looks into the tiers. Frequently, OEMs do not have good visibility into their Tier 4 and Tier 5 suppliers. A supply chain map represents the relationship between tiers of vendors and value-added production stages.

The sources of information academia, industry, and government rely on for supply chain analysis are the same: company filings and annual reports, company due diligence software, international trade statistics, bill of lading data, market research, and supply chain due diligence software. These sources of information serve as proxies policymakers can use to answer each of the aforementioned questions as well as understand the tiers of a particular supply chain, regardless of their use case or the technology in question.

Table 3. Select Sources of Information Relevant to Supply Chain Mapping

Type of Data	Example Resources
Company Filings and Annual Reports	SEC/EDGAR; Investor Relations presentations; ESG reports
Company Due Diligence Software	Dun and Bradstreet; Descartes Visual Compliance; Accurint; Experian; Equifax
International Trade/Commerce Data and Bill of Lading Information	UN Comtrade; Panjiva (now S&P Global); BACI; ImportYeti; Descartes Datamyne
Market Research Services	Bloomberg; IHS Markit (now S&P Global); IDC; Omdia; Gartner
Supply Chain Due Diligence Software	Exiger; Govini; Interos; Vertical Knowledge
Industry Association Reports and Datasets	SEMI; National Venture Capital Association; Semiconductor Industry Association

Source: Author's compilation.

While no one resource offers a complete picture of a company's operations, combining sources of information can help map a company (or technology's) supply chain. Publicly traded companies in the United States are required to disclose information about their business activities quarterly and annually. These filings, which vary in terms of length and detail, provide summaries of a company's worldwide operations, suppliers, customers, property, plants, equipment, risks, and opportunities.[52] Company due diligence software and supply chain due diligence software adds another level of granularity, providing details about specific company locations, subsidiaries, joint ventures, ownership, leadership, and risk signals (e.g., foreign ownership, control, and influence). International trade data allows for analysis of imports and exports by commodity by country, while international commerce/bill of lading data allows for analysis of imports and exports by company, by commodity, and by country. Finally, market research services summarize expert opinion regarding specific industries current competitiveness and future risks and opportunities.

Mapping Supply Chains: Methods

The sources of information presented in Table 3 are used by procurement, contracts, and compliance personnel in the public and private sectors to assess, manage, and mitigate supply chain risk. This section discusses academic, industry, and U.S. government interests in supply chains generally, as well as supply chain mapping specifically.

Academic Methods

Supply chains are studied academically in two distinct veins of research: business and economics/political science. The former field focuses on supply chain analysis in the context of procurement, logistics, warehousing, inventory, and risk management. A recent review of this literature found that the most influential supply chain papers focused on managing supply chain risks and disruptions, explaining supply chain resilience and agility, sourcing strategies, and the impact of disruptions on company activities.[53] This field of research discussed supply chain mapping, but primarily with reference to business strategies and corporate decision-making (e.g., where to build the next factory, which distributor to partner with).[54] As a result, these supply chain mapping efforts are less relevant for policymakers.

Economists and political scientists study supply chains within the context of specific technologies and global value chains (GVCs) more generally. This research crosses disciplines to look at foreign direct investment (FDI), industrialization, international trade data, technology, and the behavior of multinational corporations. Research into

GVCs frequently focuses on understanding international trade flows and multinational corporation activity: how and why international commerce is organized the way it is, how tax regimes and tariffs affect manufacturing and trade, and the role of regulations and industrial policy in technology development.[55] Research into GVCs involves mapping supply chains by industry, generally through the use of international trade data and information on stocks and flows of FDI.[56] These efforts are often relevant for policymakers interested in understanding a particular technology or how (and why) one country's competitiveness compares to another.[*]

Industry Methods

Historically, the primary focus of Supply Chain Risk Management (SCRM) has revolved around maintaining *cost*, *schedule*, and *performance*.[57] Private-sector SCRM efforts prioritize delivery of products and services on time, at the quoted cost, and to specifications ("to spec"). The use of the information presented in Table 3 by the private sector is designed to mitigate the risk that supply of the products and services needed for business operations is interrupted.

Private-sector supply chain mapping reflects an overriding focus on risk mitigation. In general, industry supply chain mapping is focused on managing company-internal products and services to ensure availability and quality. This involves creating process maps so a firm can visually represent how a product or service is sequentially delivered and by whom. As a result, the methods employed by industry achieve a remarkable level of granularity in their focus on identifying current suppliers, potential suppliers, and a wide variety of risks that may stem from these suppliers. Single- and sole-source suppliers are examples of market concentration risks, in which a small number of suppliers control the vast majority of supply of a product. Supply chain risks take many other forms, including geographic concentration, geopolitical, price and market volatility, environmental health and safety (EHS), intellectual property (IP), standards, substitution, integrity (counterfeits), and cybersecurity. Different technologies face different supply chain risks: information communications technology supply chains focus on cybersecurity risk. Raw materials supply chains focus much less on cybersecurity risk and far more on EHS risks associated with mining. Industry utilizes supply chain mapping information to characterize and mitigate these risks.

---

[*] See, for example, the public comments by Dr. Mark Dallas and Dr. Kristin Vekasi from this recent hearing on U.S.-China Competition in Global Supply Chains: Mark Dallas and Kristin Vekasi, "U.S.-China Competition in Global Supply Chains," U.S.-China Economic and Security Review Commission, June, 2022, https://www.uscc.gov/hearings/us-china-competition-global-supply-chains.

While risks that are assessed by industry may not be shared by policymakers, the detailed supply chain information that industry relies on can be useful for informing policymakers' risk analysis.

Government Methods*

The U.S. government (USG) has undertaken a wide variety of initiatives to review and manage critical technology supply chains. The most recent and visible example of USG efforts to review supply chain security are the February 2022 reports prepared by the Departments of Agriculture, Commerce, Defense, Energy, Health and Human Services, and Homeland Security in response to Executive Order 14017 on America's Supply Chains.[58] These reports, which included both 100-day and 1-year deliverables, reviewed a wide variety of critical technology supply chains in industries important to U.S. economic and national security.[59] This work followed several initiatives undertaken in the preceding five years. These efforts include Executive Order 13817 and Executive Order 13953, both of which focused on increasing critical mineral supply chain security.[60] Relatedly, Executive Order 13806 tasked the Department of Defense with analysis of its defense industrial base and supply chain resilience.[61] The Department of Commerce's Bureau of Industry and Security also maintains an industrial base assessments division that has published several reports on specific critical technologies and their supply chains in the past five years.[62] Moreover, the Government Accountability Office (GAO) regularly reviews government efforts to assess and manage supply chain risks, especially as they relate to critical technology. Recent GAO reports in 2020 and 2021 focused on government information technology supply chain risks and DOD efforts to protect critical technologies, respectively.[63]

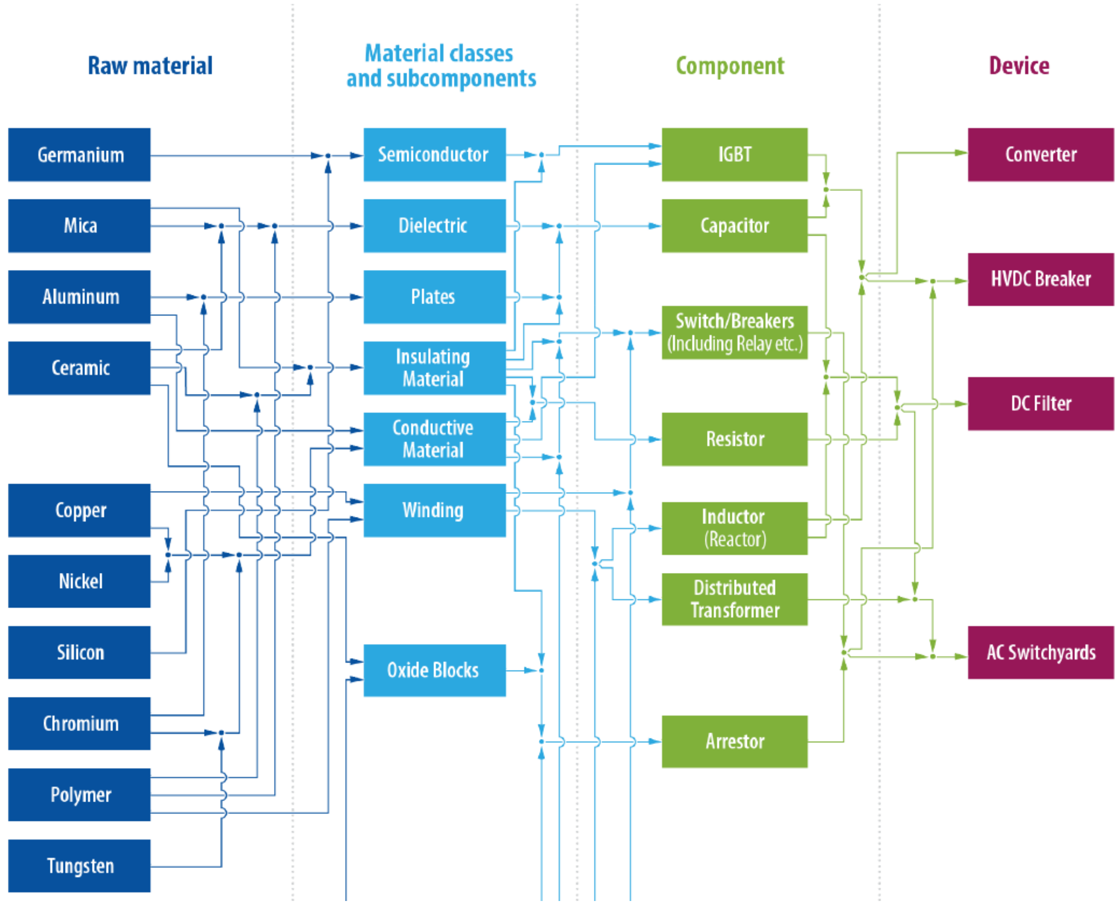
Several agencies maintain ongoing efforts to review supply chain vulnerabilities across sectors. The U.S. Geological Survey releases an annual "List of Critical Minerals" deemed important to "national security, [the] economy, renewable energy development and infrastructure."[64] The National Institute of Standards and Technology (NIST) at the Department of Commerce has produced SCRM guidelines for cybersecurity management designed to increase public and private-sector supply chain resilience.[65] NIST is also currently studying the feasibility, advisability, and costs of establishing a national supply chain database.[66] The Department of Homeland Security's Cybersecurity and Infrastructure Security Agency (CISA) has had a standing Information and Communications Technology (ICT) Supply Chain Management Task

---

* This section is derived from: John VerWey, "U.S.-China Competition in Global Supply Chains," U.S.-China Economic and Security Review Commission, June 2022, https://www.uscc.gov/sites/default/files/2022-06/John_VerWey_Testimony.pdf.

Force since December 2018.[67] The Department of Commerce is also leading the U.S. government's engagement with the European Union under the aegis of the U.S.-EU Trade and Technology Council to review critical technology supply chains and identify areas of collaboration to increase resilience.[68] Finally, the DOD produces an annual Industrial Capabilities report that presents the Department's priority industrial base risks and vulnerabilities within its supply chains.[69]

Figure 1. U.S. Government-Developed Supply Chain Map for Large Power Transformers and High Voltage Direct Current Systems[70]



Source: U.S. Department of Energy.[71]

The aforementioned government efforts map critical technology supply chains in an ad hoc manner, with various levels of granularity and fidelity (See Figure 1 for an example). These mapping efforts focus on determining specific supply chain segments and, in some cases, specific vendors and their market shares in these segments. Some of these mapping efforts are limited by a lack of access to data (which may be paywalled or simply not exist) or an inability to define the supply chain for a particular technology, which may be too nascent or emerging to have well-defined supply chain segments. In general, the supply chain vulnerabilities these reports identify are not systematically monitored or updated as supply chains change, but rather present a "snapshot in time" view.

Emerging Technology Supply Chains

Academic, industry, and government approaches to identifying emerging technologies and mapping supply chains all present partial solutions and trade-offs. Synthesizing these respective strengths helps mitigate the trade-offs of each approach: academia has developed methods for aggregating and analyzing vast networks of information on science and technology. Industry has developed methods for evaluating this information to make it actionable. And governments maintain strategic visibility across academic disciplines, industries, and countries in the context of ongoing technology competition. In addition, governments retain substantial funding and physical infrastructure to invest in particular technologies, to accelerate technology emergence, and to mitigate supply chain risks.

This section proposes a multistep technology-agnostic process policymakers could use when identifying and mapping emerging technology supply chains. It proposes that the CSET Map of Science, a tool maintained by its Emerging Technology Observatory (ETO),[*] can be used to identify particular emerging technologies exhibiting signals of "emergence" based on publication, citation, and patent activity as well as helping policymakers define specific sub-technologies of interest and the names of leading actors and institutions. It also presents the ETO's Advanced Semiconductor Supply Chain Explorer. While focused on one particular industry, the methodology behind this supply chain map is technology agnostic and could be used by policymakers interested in mapping other emerging technologies. In support of this argument, this section also presents a list of key information necessary to build a comprehensive map of a particular emerging technology supply chain.

Identifying Emerging Technologies Worth Mapping

The ETO Map of Science is a map of literature constructed by grouping research publications into research clusters (RCs) based on citation linkages.[†] RCs are groups of

---

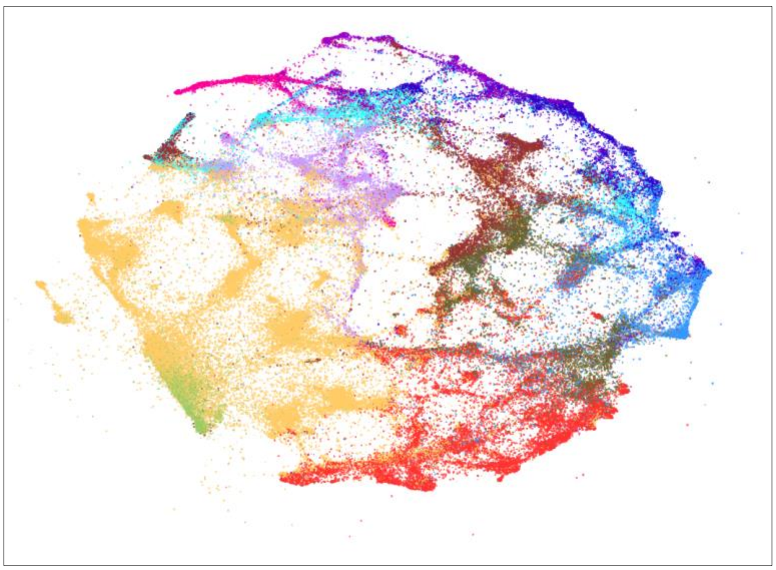
[*] The Emerging Technology Observatory is CSET's public platform for emerging technology data services.

[†] The following description is derived from: Emerging Technology Observatory, "Documentation: Map of Science," https://eto.tech/tool-docs/mos/.

articles that cite each other frequently, typically because they share common methodologies. This merged academic corpus of 270 million articles can be used for a range of analytic tasks.[72] The visualizations in the map are drawn from a set of merged scholarly literature constructed from Microsoft Academic Graph,[*] Clarivate Web of Science, the Chinese National Knowledge Infrastructure, Dimensions Digital Science, arXiv, and Papers with Code.[†] CSET clustered the merged dataset into approximately 100,000 research clusters and mapped the clusters based on shared citations (Figure 2). The tool aims to answer questions such as:

- Which areas are growing fastest?
- Which types of research are having the biggest impact?
- What are researchers in a particular country most interested in?

Figure 2. ETO's Map of Science with Color-Coded Research Clusters



Source: Emerging Technology Observatory, Map of Science.[73]

The ETO has published a variety of articles showing how the Map of Science can be used to identify emerging technologies with a level of granularity that is responsive to policymaker needs. These articles have looked at what topics are of particular interest in AI, quantum, computing hardware, and pharmacology, among others.[74] For

[*] Note: the Microsoft Academic Graph project was discontinued at the end of 2021.

[†] The data covers all years of each of these sources with the exception of papers published before 2000 in Clarivate Web of Science and papers published before 2005 in the Chinese National Knowledge Infrastructure.

policymakers interested in using the ETO's Map of Science to identify potential emerging technologies, these articles provide a replicable methodology:

- Select subject(s) of interest
- Filter the results for specific characteristics:
    - "Emerging" RCs (an average article age of five years or newer)
    - "Growing" RCs (a large number [>100 in preceding five years] of recent articles)
    - "Impactful" RCs (research that gets cited frequently [a citation rate that exceeds the median across all Map of Science clusters])
- Switch to the map's list view and sort by growth rating
- Review specific research clusters

The results of these filters will show policymakers research areas that, in some cases, represent particular technologies that display characteristics of emergence: novelty, growth, and impact. In addition, the results will provide a list of high-impact articles along with author affiliation (university, firm, or government), patents that cite to these articles, and which entities "lead" in a particular RC. The names of specific researchers, research institutions, and firms is helpful information for policymakers interested in taking the next step and mapping a particular emerging technology's supply chain.

Mapping Emerging Technology Supply Chains

Mapping an emerging technology's supply chain is a three-step process: (1) establish a basic understanding of the ecosystem (what currently exists, how it is used, what knowledge gaps remain); (2) analyze the particular subsegment(s) of interest; and (3) build a map to represent the findings. Each of these steps requires successively more detailed information. Because nearly all emerging technology development is occurring in universities and private firms, it is a matter of collecting names, mapping relationships, quantifying progress, and assessing trends.

Basic Industry Mapping

Establishing a basic understanding of an emerging technology supply chain begins with identifying key concepts and actors. The ETO's Map of Science can help policymakers establish a basic understanding and answer questions such as:[*]

- What are the unique terms associated with the technology?
  - Micro: Create a glossary of technology-specific terms.
  - Macro: How do these terms relate to the broader field of science and technology?
- Which individuals and firms are "expert" in this field?
  - What are their affiliations (university, private sector, government)?
  - What metrics can be used to represent this "expertise"?
- What is the broader community of interest?
  - Where is the leading research published, presented, and standardized (journals, conferences)?
  - What open-source data exists and where can it be found (blogs, forums)?
  - What proprietary resources exist (industry publications)?
- How does this technology relate to other technologies?
  - Is this technology an outgrowth of a previously existing field of research or a completely new field?
  - Are there past incarnations of this industry that can be used to benchmark the pace of progress?

Detailed Market Analysis

Once a basic understanding of an emerging technology ecosystem has been established, a more detailed analysis of the subsegments follows. This detailed industry assessment will (ideally) also leverage historic data to establish trends and the rate of progress.

- Who are the current leading actors?
  - Where are these actors physically located?
  - Is this lead observable via publication and citation intensity, patent filings, funding rounds, grants, or other quantifiable metrics? If so, capture them.

---

[*] This section is loosely derived from: Steve Blank, "Mapping the Unknown – The Ten Steps to Map Any Industry," Steve Blank, September 20, 2022, https://steveblank.com/2022/09/20/mapping-the-unknown-the-ten-steps-to-map-any-industry/.

    - How long have they been leading?
- How does the technology “stack”?
    - Who builds on top of whom?
    - What are the enabling tools and technologies on which this emerging technology relies?
        - How substitutable are these tools?
- Competitiveness
    - Who are the tiers of suppliers?
    - Who is the ultimate customer for this technology (were it to “emerge”)?
    - What barriers to entry exist, is there potential for new entrants, and, if so, under what circumstances?
    - What is the current level of funding by actor by country (public R&D, private firm capital expenditures)?
    - How does the domestic workforce compare internationally, does workforce enable or constrain development in this industry?

Constructing a Technology Supply Chain Map

Once a detailed understanding of the industry has been established, it is possible to construct a map that represents both the flow of a particular technology product/service and overall competitiveness. This map will represent the directional flow of actors involved in a particular technology’s development scaled by prominence and with reference to geographic distribution and competitiveness. The ETO’s recently introduced Supply Chain Explorer for Advanced Semiconductors provides a model of this mapping in practice.[75]

Previous CSET research has described the complexity of the semiconductor supply chain in detail.[76] The Supply Chain Explorer was developed for policymakers interested in assessing the utility of policies to protect (which semiconductor technologies to restrict sales of) and promote (which nascent semiconductor technologies hold future promise worth investing in). The information on which the supply chain explorer is based aligns with the questions posed in the preceding section. This includes information on unique terms, firm-level leadership, and market share by subsegment, geographic headquarters location, the technology flow from design to fabrication, key choke points, and substitutability (or lack thereof). Specifically, the supply chain explorer can be used to:[77]

- Learn about how advanced logic chips are produced and the tools, materials, and processes that are involved.

- Visually explore the chip supply chain as a series of stages and processes, each involving different tools, materials, and providers.
- Assess countries' and companies' role in the supply chain using the dataset's extensive provider information.
- Identify "choke points," market concentration, dependency relationships, and other structural features of the supply chain.

It is also possible for users to highlight specific elements:[78]

- The **Supplier Countries** filter highlights stages and inputs according to the cumulative market share of the selected country or countries. (A country's market share is equal to the total market share of companies headquartered in that country.)
- The **Supplier Companies** filter is a binary filter that highlights stages and elements supplied (to any extent) by the selected company, or (if more than one company is selected) by any one of the selected companies.
- The **Market Concentration** filter highlights stages and inputs according to how many countries supply them. There are three different shades of highlighting. For example, the darkest shade is applied if suppliers in a single country control more than 75 percent of the total market.

All of this information comes with important caveats. Policymakers interested in identifying emerging technologies and mapping their supply chains will need to carefully supplement the data provided in the ETO's Map of Science and Supply Chain Explorer with additional information derived from sources described in earlier sections of this paper. For example, information on trends in talent flows and investment funding can supplement these tools, assisting policymakers' efforts to identify emerging technologies and map key entities involved in associated supply chains.

Conclusion

Policymakers are asking questions of techno-economic competitiveness that draw on sources of information and best practices used by academia, industry, and government to identify emerging technologies and analyze supply chains. There are a variety of proposals under consideration to establish new functions within the U.S. government to protect and promote emerging technology innovation as well as supply chain resilience. These efforts should be closely coordinated. The ETO's Map of Science and Supply Chain Explorer offer a model policymakers can use for mapping emerging technology supply chains. The ETO's Map of Science can help policymakers identify technologies that exhibit signs of emergence. The supply chain explorer, though currently focused on advanced semiconductors, employs a methodology that is technology agnostic. Combined, these tools and methodology can assist policymakers interested in identifying and mapping emerging technology supply chains.

Author

John VerWey is a non-resident research fellow at CSET and an East Asia national security advisor at Pacific Northwest National Laboratory.

Acknowledgments

For helpful feedback and suggestions, the author would like to thank Igor Mikolic-Torreira, Richard Danzig, Kevin O'Toole, Sabra Simmonds, Taylore Roth, Zachary Arnold, Catherine Aiken, and Melissa Flagg. He would also like to thank Matt Mahoney, Jahnavi Mukul, Chloe Moffett, Tessa Baker, Shelton Fitch, and Owen Daniels for editorial support.

Document Identifier: doi: 10.51593/20230004

Appendix 1. Recent U.S. Government Requests for Comment/Information (RFCs, RFIs) Related to Supply Chains and Strategies to Protect and Promote Emerging Technologies[79]

	Title	Agency	Date
Supply Chain RFCs and RFIs	Notice of Request for Comments on Executive Order "America's Supply Chains"	Department of Defense	2021
	Notice of Request for Public Comments on Risks in the Information Communications Technology Supply Chain	Department of Commerce/Department of Homeland Security	2021
	Notice of Request for Information (RFI) on Energy Sector Supply Chain Review	Department of Energy	2021
	Notice of Request for Information (RFI) on Risks in the High-Capacity Batteries, Including Electric Vehicle Batteries Supply Chain	Department of Energy	2021
	Supply Chains for the Production of Agricultural Commodities and Food Products	Department of Agriculture	2021
	America's Supply Chains and the Transportation Industrial Base	Department of Transportation	2021
	Risks in the Semiconductor Manufacturing and Advanced Packaging Supply Chain	Department of Commerce	2021
	Request for Public Comments on Supply Chain Issues To Support the U.S.-EU Trade and Technology Council Secure Supply Chains Working Group	Department of Commerce	2022
	Access to Fertilizer: Competition and Supply Chain Concerns	Department of Agriculture	2022
	Joint FERC-DOE Supply Chain Risk Management, Technical Conference; Supplemental Notice of Technical Conference	Department of Energy/FERC	2022

Emerging Technology Protect and Promote RFCs and RFIs	Review of Controls for Certain Emerging Technologies	Department of Commerce	2018
	Identification and Review of Controls for Certain Foundational Technologies	Department of Commerce	2020
	The National Strategy to Secure 5G Implementation Plan	Department of Commerce	2020
	Request for Comments Concerning the Imposition of Export Controls on Certain Brain-Computer Interface (BCI) Emerging Technology	Department of Commerce	2021
	Request for Comments Concerning the Imposition of Section 1758 Technology Export Controls on Instruments for the Automated Chemical Synthesis of Peptides	Department of Commerce	2022
	Request for Information; National Biotechnology and Biomanufacturing Initiative	White House Office of Science and Technology Policy	2022
	Accelerating Innovations in Emerging Technologies	Department of Energy	2022
	Request for Comments on Artificial Intelligence Export Competitiveness	Department of Commerce	2022
	Public Wireless Supply Chain Innovation Fund Implementation	Department of Commerce	2022
	Controls on Certain Marine Toxins	Department of Commerce	2022

Appendix 2. Emerging Technology Attributes

Table 5. Emerging Technology Attributes

Characteristic	Concept	Example
Radical novelty	Innovation that is clearly differentiated from past technologies	Wireless communication technologies
Fast growth	An increase in the number of actors, funding, and/or outputs	Quantum computing
Coherence	Convergence of previously separated research streams	CRISPR-based gene editing
Prominent impact	Potential to create an entirely new industry, or fundamentally change an existing one	Google's PageRank algorithm
Uncertainty or ambiguity	A variety of potential applications may appear, but high-confidence future predictions are difficult	Biofuels

Source: Daniele Rotolo, Diana Hicks, and Ben R. Martin, "What Is an Emerging Technology?"

Radical novelty refers to a technology's newness or distinctiveness: how an innovation is clearly differentiated from past technologies. However, this novelty may also come in the form of employing an existing technology for an entirely new purpose. One example of this is wireless communication technology, which began as a lab-based tool for measuring electromagnetic waves and was then used to enable communication between remote locations (e.g., lighthouses), and evolved to transmit audio and data via wireless fidelity (Wi-Fi) standards.[80]

Fast growth is observable through the number of actors involved (e.g., scientists, universities, firms, public users), public and private funding, knowledge outputs (publications, patents), and pilot projects. Measuring growth requires caveats, and in general it is preferable that a particular technology's growth be measured relative to others'. For example, comparing publication rates and funding levels devoted to quantum computing in the 1990s versus the 2010s suggests a level of growth that may indicate quantum technologies are emerging.

Coherence refers to "convergence of previously separated research streams" and the establishment of a distinct community of practice engaged in the technology's development separate from "parent" technologies.[81] For example, the characterization of CRISPR-Cas systems beginning in the late 1980s and into the early 1990s resulted in a new subfield of biotechnology focused on gene editing technologies and a new academic discipline within biology.[82]

Prominent impact refers to a technologies' ability to create an entirely new industry or transform an existing one, especially one with large economic implications. For example, Google's PageRank algorithm, which employed a novel method of ranking web-based search results, reorganized how people and organizations did business on the internet.[83]

Finally, uncertainty or ambiguity refers to a given technology's inherently unknowable application(s) and impact(s). One criterion that distinguishes an emerging technology from an "emerged" technology is this ambiguity. For example, the development of biofuels for use in commercial aircraft jet engines may find success in the aviation industry, it may find success in another entirely separate fuel-consuming industry, or it may fail to realize its technical promise entirely. This uncertain outcome is part of what makes biofuels emerging as opposed to jet engines, where the underlying technology has not changed radically in decades and has "emerged."

Endnotes

[1] The White House, *National Strategy for Critical and Emerging Technologies*, October 2020, https://trumpwhitehouse.archives.gov/wp-content/uploads/2020/10/National-Strategy-for-CET.pdf; The White House, *Technologies for American Innovation and National Security*, February 7, 2022, https://www.whitehouse.gov/ostp/news-updates/2022/02/07/technologies-for-american-innovation-and-national-security/.

[2] Maxwell Bernstein, "It's Colossal: Creating the World's Largest Dilution Refrigerator," Fermilab, December 7, 2022, https://news.fnal.gov/2022/12/its-colossal-creating-the-worlds-largest-dilution-refrigerator/; "Homepage," Maybell Quantum, https://www.maybellquantum.com/.

[3] 2-2-2 and Natsec Tech by SCSP, "SCSP Newsletter Edition 4 Addendum," SCSP Substack, May 19, 2022, https://scsp222.substack.com/p/scsp-newsletter-edition-4-addendum?s=w.

[4] 2-2-2 and Natsec Tech by SCSP, "What's in a Tech List?" SCSP Substack, May 19, 2022, https://scsp222.substack.com/p/whats-in-a-tech-list.

[5] Richard Danzig, "Driving in the Dark: Ten Propositions about Prediction and National Security," (Center for New American Security, October 26, 2011), https://www.cnas.org/publications/reports/driving-in-the-dark-ten-propositions-about-prediction-and-national-security%C2%A0.

[6] Hermann Simon, *Hidden Champions of the Twenty-First Century: The Success Strategies of Unknown World Market Leaders* (New York: Springer, 2009), https://link.springer.com/book/10.1007/978-0-387-98147-5.

[7] "Explore the possibilities of Quantum," Quantum AI Google, Accessed May 24, 2023, https://quantumai.google/; Sara Fischer, "Slow Fade for Google and Meta's Ad Dominance," Axios, December 20, 2022, https://www.axios.com/2022/12/20/google-meta-duopoly-online-advertising.

[8] United States House Code, "Chapter 58: Export Control Reform," Accessed May 24, 2023, https://uscode.house.gov/view.xhtml?path=/prelim@title50/chapter58&edition=prelim; Export Control Law of the People's Republic of China, "Order of the President of the People's Republic of China," October 17, 2020, http://www.npc.gov.cn/englishnpc/c23934/202112/63aff482fece44a591b45810fa2c25c4.shtml.

[9] Federal Register, *Review of Controls for Certain Emerging Technologies*, (Washington, D.C.: Industry and Security Bureau, November 19, 2018), https://www.federalregister.gov/documents/2018/11/19/2018-25221/review-of-controls-for-certain-emerging-technologies.

[10] Federal Register, *Identification and Review of Controls for Certain Foundational Technologies*, (Washington, D.C.: Industry and Security Bureau, August 27, 2020), https://www.federalregister.gov/documents/2020/08/27/2020-18910/identification-and-review-of-controls-for-certain-foundational-technologies.

[11] United States House Code, "Section 1758 of Chapter 58: Export Control Reform," Accessed May 24, 2023, https://uscode.house.gov/view.xhtml?path=/prelim@title50/chapter58&edition=prelim.

[12] Federal Register, *Commerce Control List: Controls on Certain Marine Toxins*, (Washington, D.C.: Industry and Security Bureau, May 23, 2022), https://www.federalregister.gov/documents/2022/05/23/2022-10907/commerce-control-list-controls-on-certain-marine-toxins;
Bureau of Industry and Security, *Update Conference on Export Controls and Policy*, (Washington, D.C.: Department of Commerce, June 29, 2022), https://www.bis.doc.gov/index.php/component/docman/?task=doc_download&gid=3073.

[13] Congressional Research Service, "Frequently Asked Questions: CHIPS Act of 2022 Provisions and Implementation" (Washington, D.C.: Congressional Research Service, April 25, 2023), https://crsreports.congress.gov/product/pdf/R/R47523; Julie Zhu, "Exclusive: China readying $143 billion package for its chip firms in face of U.S. curbs," Reuters, December 13, 2022, https://www.reuters.com/technology/china-plans-over-143-bln-push-boost-domestic-chips-compete-with-us-sources-2022-12-13/.

[14] "Category Archives: Philosophy of Science," Internet Encyclopedia of Philosophy, https://iep.utm.edu/category/s-l-m/science/.

[15] Patrick Collison and Tyler Cowen, "We Need a New Science of Progress," *The Atlantic*, July 30, 2019, https://www.theatlantic.com/science/archive/2019/07/we-need-new-science-progress/594946/.

[16] Ian Miles, "The Development of Technology Foresight: A Review," *Technological Forecasting and Social Change* 77, Issue 9 (November 2010): 1448–1456, https://www.sciencedirect.com/science/article/pii/S0040162510001794.

[17] Amos Golan, *Foundations of Info-Metrics: Modeling, Inference, and Imperfect Information* (Oxford: Oxford University Press, 2017), https://academic.oup.com/book/43689.

[18] John Mingers and Loet Leydesdorff, "A Review of Theory and Practice in Scientometrics," *European Journal of Operational Research* 246, Issue 1, (October 2015): 1–19, https://www.sciencedirect.com/science/article/pii/S037722171500274X.

[19] R.N. Broadus, "Toward a Definition of Bibliometrics," *Scientometrics* 12, (November 1987): 373–379, https://link.springer.com/article/10.1007/BF02016680.

[20] Committee on Network Science for Future Army Applications, Board on Army Science and Technology, Division on Engineering and Physical Sciences, National Research Council of the National Academies, "Network Science" (Washington, D.C.: The National Academies Press, 2005), https://nap.nationalacademies.org/catalog/11516/network-science.

[21] Daniele Rotolo, Diana Hicks, and Ben R. Martin, "What Is an Emerging Technology?" arXiv:1503.00673v4 (2015), https://arxiv.org/abs/1503.00673.

[22] Karen White, "Publications Output: U.S. Trends and International Comparisons," Science & Engineering Indicators, October 28, 2021, https://ncses.nsf.gov/pubs/nsb20214/publication-output-by-country-region-or-economy-and-scientific-field.

[23] U.S. Patent and Trademark Office, Patent Technology Monitoring Team (PTMT), "U.S. Patent Statistics Chart Calendar Years 1963-2020," https://www.uspto.gov/web/offices/ac/ido/oeip/taf/us_stat.htm.

[24] H.D. White and K.W. McCain, "Visualization of Literatures," Annual Review of Information Science and Technology (ARIST), 1997.

[25] Michael E. Bales, Drew N. Wright, Peter R., and Terrie R. Wheeler, "Bibliometric Visualization and Analysis Software: State of the Art, Workflows, and Best Practices," (2020), https://ecommons.cornell.edu/handle/1813/69597.

[26] Bales et al., "Bibliometric Visualization and Analysis Software."

[27] Deutsche Bank, "Horizon Scanning with Deutsche Bank," Apple Podcasts, https://podcasts.apple.com/us/podcast/horizon-scanning-with-deutsche-bank/id1574303731.

[28] "Transformation," *ToughTech* 07, (Fall 2021), https://cdn2.assets-servd.host/the-engine/production/Reports-and-Publications/TT07_Transformation.pdf.

[29] Josh Lerner and Ramana Nanda, "Venture Capital's Role in Financing Innovation: What We Know and How Much We Still Need to Learn," *Journal of Economic Perspectives* 34, no. 3, (Summer 2020): 237–261, https://www.aeaweb.org/articles?id=10.1257/jep.34.3.237.

[30] Special Competitive Studies Project, "Platforms Panel Interim Panel Report: Harnessing the New Geometry of Innovation" (Special Competitive Studies Project, November 2022), 25, https://www.scsp.ai/2022/11/scsps-platform-panel-releases-interim-panel-report/.

[31] National Academies, "Leveraging the Future Research and Development Ecosystem for the Intelligence Community," Accessed May 24, 2023, https://www.nationalacademies.org/our-work/leveraging-the-future-research-and-development-ecosystem-for-the-intelligence-community.

[32] Amy Webb, "Why the government needs a Department of the Future," Politico, December 13, 2016, https://www.politico.com/agenda/story/2016/12/department-of-future-trump-000258/.

[33] European Commission, Joint Research Centre, *Weak signals in science and technologies in 2021 – Technologies at a very early stage of development that could impact the future*, (Brussels: Publications Office of the European Union, 2022), https://op.europa.eu/en/publication-detail/-/publication/f5a243d0-24eb-11ed-8fa0-01aa75ed71a1.

[34] European Commission, Joint Research Centre, *Weak signals in science and technologies – 2019 report: technologies at a very early stage of development that could impact the future*, (Brussels: Publications Office of the European Union, 2019), https://op.europa.eu/en/publication-detail/-/publication/e95696bd-157e-11ea-8c1f-01aa75ed71a1/language-en/format-PDF/source-search.

[35] European Commission, *Text Mining and Analysis Competence Centre*, (Brussels: European Union, 2021), https://knowledge4policy.ec.europa.eu/text-mining/information_systems_en.

[36] European Commission, *Supply chain of renewable energy technologies in Europe: An analysis for wind, geothermal and ocean energy*, (Brussels: European Union, 2017), https://publications.jrc.ec.europa.eu/repository/handle/JRC108106; Elisa Carelli, "Presentation from the JRC of its tool on supply chain raw materials, discussion about the disruption on plastics supply chain," European Cluster Collaboration Platform, May 29, 2020, https://clustercollaboration.eu/forum-covid/european-alliance-against-coronavirus-daily-meetings/presentation-jrc-its-tool-supply-chain-raw-materials-discussion-about-disruption.

[37] Science and Technology, *Horizon Scanning*, (Washington, D.C.: Department of Homeland Security, 2022), https://www.dhs.gov/science-and-technology/horizon-scanning.

[38] Office of the Undersecretary of Defense for Research and Engineering, "Critical Technology Areas," https://www.cto.mil/usdre-strat-vision-critical-tech-areas/.

[39] U.S. Government Accountability Office, "Science, Technology Assessment, and Analytics at GAO," September 7, 2022, https://www.gao.gov/products/gao-22-900426.

[40] Michael T. Gibbons, "Federally Funded R&D Centers Report 6% Increase in R&D Spending in FY 2021," National Center for Science and Engineering Statistics, July 28, 2022, https://ncses.nsf.gov/pubs/nsf22334.

[41] Congressional Research Service, "Federally Funded Research and Development Centers (FFRDCs): Background and Issues for Congress," (Washington, D.C.: Congressional Research Service, April 3, 2020), https://crsreports.congress.gov/product/pdf/R/R44629/6.

[42] National Science Foundation, "About NSF," https://www.nsf.gov/about/how.jsp.

[43] Intelligence Advanced Research Projects Activity, *Foresight and Understanding from Scientific Exposition*, (Washington, D.C.: Office of the Director of National Intelligence), https://www.iarpa.gov/research-programs/fuse.

[44] Intelligence Advanced Research Projects Activity, *Forest Forecasting Science & Technology*, (Washington, D.C.: Office of the Director of National Intelligence), https://www.iarpa.gov/research-programs/forest.

[45] Special Competitive Studies Project, "Platforms Panel Interim Panel Report: Harnessing the New Geometry of Innovation," 27.

[46] "Mid-Decade Challenges to National Competitiveness" (Special Competitive Studies Project, September, 2022), 163, https://www.scsp.ai/wp-content/uploads/2022/09/SCSP-Mid-Decade-Challenges-to-National-Competitiveness.pdf; Special Competitive Studies Project, "Platforms Panel Interim Panel Report: Harnessing the New Geometry of Innovation," 55.

[47] This turn of phrase is borrowed from Dr. Mark P. Dallas. Mark P. Dallas, "U.S.-China Competition in Global Supply Chains," U.S.-China Economic and Security Review Commission, June 9, 2022, 5, https://www.uscc.gov/sites/default/files/2022-06/Mark_Dallas_Testimony.pdf.

[48] Regulations.gov, *Comment on FR Doc # 2018-25221*, (Washington, D.C.: Bureau of Industry and Security, February 21, 2019), https://www.regulations.gov/comment/BIS-2018-0024-0160.

[49] Margaret Mann, Vicky Putsche and Benjamin Shrager, *Grid Energy Storage Supply Chain Deep Dive Assessment*, (Washington, D.C.: Department of Energy, February 24, 2022), https://www.energy.gov/sites/default/files/2022-02/Energy%20Storage%20Supply%20Chain%20Report%20-%20final.pdf.

[50] "Containers," Lloyd's List, https://www.lloydsloadinglist.com/freight-directory/news/Air-freight-boost-from-rise-in-semiconductor-shipments/70200.htm.

[51] Benjamin Thompson and Noah Baker, "Google AI beats humans at designing computer chips," *Nature Podcast*, June 9, 2021, https://www.nature.com/articles/d41586-021-01558-y.

[52] Investor.gov, *Form 10-K*, (Washington, D.C.: U.S. Securities and Exchange Commission), https://www.investor.gov/introduction-investing/investing-basics/glossary/form-10-k.

[53] K. Katsaliaki, P. Galetsi, and S. Kumar, *Supply chain disruptions and resilience: a major review and future research agenda*, (Washington, D.C.: National Center for Biotechnology Information, 2021), https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7792559/.

[54] John T. Gardner and Martha C. Cooper, "Strategic Supply Chain Mapping Approaches," *Journal of Business Logistics* 24, no. 2, (2003): 37–64, https://onlinelibrary.wiley.com/doi/abs/10.1002/j.2158-1592.2003.tb00045.x.

[55] Pol Antràs and Davin Chor, "Global Value Chains," National Bureau of Economic Research, March, 2021, https://www.nber.org/papers/w28549.

[56] John T. Gardner and Martha C. Cooper, "Strategic Supply Chain Mapping Approaches," *Journal of Business Logistics* 24, no. 2, (2003): 37–64, https://onlinelibrary.wiley.com/doi/abs/10.1002/j.2158-1592.2003.tb00045.x.

[57] Chris Nissen, John Gronager, Robert Metzger, and Harvey Rishikof, "Deliver Uncompromised A Strategy for Supply Chain Security and Resilience in Response to the Changing Character of War," (Mitre, August, 2018), https://www.dni.gov/files/NCSC/documents/supplychain/20190327-Deliver-uncompromised.pdf.

[58] Exec. Order No. 14017, 86 FR 11849 (2021), https://www.whitehouse.gov/briefing-room/presidential-actions/2021/02/24/executive-order-on-americas-supply-chains/.

[59] The White House, "The Biden-Harris Plan to Revitalize American Manufacturing and Secure Critical Supply Chains in 2022," February 24, 2022, https://www.whitehouse.gov/briefing-room/statements-

releases/2022/02/24/the-biden-harris-plan-to-revitalize-american-manufacturing-and-secure-critical-supply-chains-in-2022/.

[60] Federal Register, *A Federal Strategy To Ensure Secure and Reliable Supplies of Critical Minerals*, (Washington, D.C.: Executive Office of the President, December 26, 2017), https://www.federalregister.gov/documents/2017/12/26/2017-27899/a-federal-strategy-to-ensure-secure-and-reliable-supplies-of-critical-minerals; Federal Register, *Addressing the Threat to the Domestic Supply Chain From Reliance on Critical Minerals From Foreign Adversaries and Supporting the Domestic Mining and Processing Industries*, (Washington, D.C.: Executive Office of the President, October 5, 2020), https://www.federalregister.gov/documents/2020/10/05/2020-22064/addressing-the-threat-to-the-domestic-supply-chain-from-reliance-on-critical-minerals-from-foreign.

[61] Federal Register, *Assessing and Strengthening the Manufacturing and Defense Industrial Base and Supply Chain Resiliency of the United States*, (Washington, D.C.: Executive Office of the President, July 26, 2017), https://www.federalregister.gov/documents/2017/07/26/2017-15860/assessing-and-strengthening-the-manufacturing-and-defense-industrial-base-and-supply-chain.

[62] Bureau of Industry and Security, *Industrial Base Assessments*, (Washington, D.C.: Department of Commerce), https://www.bis.doc.gov/index.php/other-areas/office-of-technology-evaluation-ote/industrial-base-assessments.

[63] U.S. Government Accountability Office, "Information Technology: Federal Agencies Need to Take Urgent Action to Manage Supply Chain Risks," December 15, 2020, https://www.gao.gov/products/gao-21-171; U.S. Government Accountability Office, "DOD Critical Technologies Plans for Communicating, Assessing, and Overseeing Protection Efforts Should Be Completed," January, 2021, https://www.gao.gov/assets/gao-21-158.pdf.

[64] Communications and Publishing, *U.S. Geological Survey Releases 2022 List of Critical Minerals*, (Washington, D.C.: U.S. Geological Survey, February 22, 2022), https://www.usgs.gov/news/national-news-release/us-geological-survey-releases-2022-list-critical-minerals.

[65] "NIST Updates Cybersecurity Guidance for Supply Chain Risk Management," National Institute of Standards and Technology, May 5, 2022, https://www.nist.gov/news-events/news/2022/05/nist-updates-cybersecurity-guidance-supply-chain-risk-management.

[66] "NIST Provisions in the National Defense Authorization Act of 2021," National Institute of Standards and Technology, https://www.nist.gov/document/chart.

[67] "ICT Supply Chain Risk Management Task Force," Cybersecurity & Infrastructure Security Agency, https://www.cisa.gov/ict-scrm-task-force.

[68] Office of Public Affairs, *U.S.-EU Joint Statement of the Trade and Technology Council*, (Washington, D.C.: Department of Commerce, May 16, 2022), https://www.commerce.gov/news/press-releases/2022/05/us-eu-joint-statement-trade-and-technology-council.

[69] Office of Public Affairs, *DOD Releases Industrial Capabilities Report*, (Washington, D.C.: Department of Defense, January 14, 2021), https://www.defense.gov/News/Releases/Release/Article/2472854/dod-releases-industrial-capabilities-report/.

[70] Ruby Nguyen, Mike Severson, Bo Zhang, Bjorn Vaagensmith, Md Mamunur Rahman, Ange-Lionel Toba, Paige Price, Ryan Davis, and Sophie Williams, *Electric Grid Supply Chain Review: Large Power Transformers and High Voltage Direct Current Systems*, (Washington, D.C.: Department of Energy, February 24, 2022), https://www.energy.gov/sites/default/files/2022-02/Electric%20Grid%20Supply%20Chain%20Report%20-%20Final.pdf.

[71] Nguyen et al., *Electric Grid Supply Chain Review*.

[72] Refer to the Data Snapshot series for more information: Center for Emerging Technology and Security, "Data Snapshot," https://cset.georgetown.edu/publications/?fwp_content_type=data-snapshot#publications; https://eto.tech/dataset-docs/mac/; NOTE: "Data sourced from Dimensions, an inter-linked research information system provided by Digital Science (http://www.dimensions.ai)" and "All China National Knowledge Infrastructure content is furnished for use in the United States by East View Information Services, Minneapolis, MN, USA."

[73] Emerging Technology Observatory, Map of Science, https://sciencemap.eto.tech/?mode=map.

[74] Emerging Technology Observatory, "What's hot in materials science? Discovering emerging topics with ETO's Map of Science," November 29, 2022, https://eto.tech/blog/whats-hot-in-materials-science-map-of-science/; Emerging Technology Observatory, "What's hot in quantum? Discovering emerging topics with ETO's Map of Science," December 1, 2022, https://eto.tech/blog/whats-hot-in-quantum-map-of-science/; Emerging Technology Observatory, "What's hot in hardware? Discovering emerging topics with ETO's Map of Science," December 7, 2022, https://eto.tech/blog/whats-hot-in-computing-hardware-map-of-science/; Emerging Technology Observatory, "What's hot in Chinese AI Research? Discovering emerging topics with ETO's Map of Science," December 12, 2022, https://eto.tech/blog/whats-hot-in-chinese-ai-map-of-science/; Emerging Technology Observatory, "What's hot in Pharmacology? Discovering emerging topics with ETO's Map of Science," December 16, 2022, https://eto.tech/blog/whats-hot-in-pharmacology-map-of-science/.

[75] Emerging Technology Observatory, "Supply Chain Explorer," October 16, 2022, https://chipexplorer.eto.tech/; Emerging Technology Observatory, "Documentation: Supply Chain Explorer: Advanced Chips," https://eto.tech/tool-docs/chipexplorer/.

[76] Saif M. Khan, "Securing Semiconductor Supply Chains," Center for Security and Emerging Technology, January 2021, https://cset.georgetown.edu/publication/securing-semiconductor-supply-chains/.

[77] Emerging Technology Observatory, "A guide for the perplexed: introducing the Supply Chain Explorer," October 3, 2022, https://eto.tech/blog/introducing-supply-chain-explorer-advanced-chips/.

[78] Emerging Technology Observatory, "Documentation: Supply Chain Explorer: Advanced Chips," https://eto.tech/tool-docs/chipexplorer/.

[79] Federal Register, *Notice of Request for Comments on Executive Order "America's Supply Chains*," (Washington, D.C.: Defense Department, April 13, 2021),

https://www.federalregister.gov/documents/2021/04/13/2021-07539/notice-of-request-for-comments-on-executive-order-americas-supply-chains;
Federal Register, *Notice of Request for Public Comments on Risks in the Information Communications Technology Supply Chain*, (Washington, D.C.: Department of Commerce, September 20, 2021), https://www.federalregister.gov/documents/2021/09/20/2021-20229/notice-of-request-for-public-comments-on-risks-in-the-information-communications-technology-supply;
Federal Register, *Notice of Request for Information (RFI) on Energy Sector Supply Chain Review*, (Washington, D.C.: Department of Energy, November 29, 2021), https://www.federalregister.gov/documents/2021/11/29/2021-25898/notice-of-request-for-information-rfi-on-energy-sector-supply-chain-review;
Federal Register, *Notice of Request for Information (RFI) on Risks in the High-Capacity Batteries, Including Electric Vehicle Batteries Supply Chain*, (Washington, D.C.: Department of Energy, March 29, 2021), https://www.federalregister.gov/documents/2021/03/29/2021-06337/notice-of-request-for-information-rfi-on-risks-in-the-high-capacity-batteries-including-electric;
Federal Register, *Supply Chains for the Production of Agricultural Commodities and Food Products*, (Washington, D.C.: Agricultural Marketing Service, April 21, 2021), https://www.federalregister.gov/documents/2021/04/21/2021-08152/supply-chains-for-the-production-of-agricultural-commodities-and-food-products;
Federal Register, *America's Supply Chains and the Transportation Industrial Base*, (Washington, D.C.: Department of Transportation, September 16, 2021), https://www.federalregister.gov/documents/2021/09/16/2021-19974/americas-supply-chains-and-the-transportation-industrial-base;
Federal Register, *Risks in the Semiconductor Manufacturing and Advanced Packaging Supply Chain*, (Washington, D.C.: Department of Commerce, March 15, 2021), https://www.federalregister.gov/documents/2021/03/15/2021-05353/risks-in-the-semiconductor-manufacturing-and-advanced-packaging-supply-chain;
Federal Register, *Request for Public Comments on Supply Chain Issues To Support the U.S.-EU Trade and Technology Council Secure Supply Chains Working Group*, (Washington, D.C.: Department of Commerce, April 6, 2022), https://www.federalregister.gov/documents/2022/04/06/2022-07211/request-for-public-comments-on-supply-chain-issues-to-support-the-us-eu-trade-and-technology-council;
Federal Register, *Access to Fertilizer: Competition and Supply Chain Concerns*, (Washington, D.C.: Agricultural Marketing Service, March 17, 2022), https://www.federalregister.gov/documents/2022/03/17/2022-05670/access-to-fertilizer-competition-and-supply-chain-concerns;
Federal Register, *Joint FERC-DOE Supply Chain Risk Management*, *Technical Conference; Supplemental Notice of Technical Conference*, (Washington, D.C.: Federal Energy Regulatory Commission, November 14, 2022), https://www.federalregister.gov/documents/2022/11/14/2022-24710/joint-ferc-doe-supply-chain-risk-management-technical-conference-supplemental-notice-of-technical;
Federal Register, *Review of Controls for Certain Emerging Technologies*, (Washington, D.C.: Department of Commerce, November 19, 2018), https://www.federalregister.gov/documents/2018/11/19/2018-25221/review-of-controls-for-certain-emerging-technologies;
Federal Register, *Identification and Review of Controls for Certain Foundational Technologies*, (Washington, D.C.: Department of Commerce, August 27, 2020), https://www.federalregister.gov/documents/2020/08/27/2020-18910/identification-and-review-of-controls-for-certain-foundational-technologies;

Federal Register, *The National Strategy to Secure 5G Implementation Plan*, (Washington, D.C.: Department of Commerce, May 28, 2020), https://www.federalregister.gov/documents/2020/05/28/2020-11398/the-national-strategy-to-secure-5g-implementation-plan;
Federal Register, *Request for Comments Concerning the Imposition of Export Controls on Certain Brain-Computer Interface (BCI) Emerging Technology*, (Washington, D.C.: Department of Commerce, October 26, 2021), https://www.federalregister.gov/documents/2021/10/26/2021-23256/request-for-comments-concerning-the-imposition-of-export-controls-on-certain-brain-computer;
Federal Register, *Request for Comments Concerning the Imposition of Section 1758 Technology Export Controls on Instruments for the Automated Chemical Synthesis of Peptides*, (Washington, D.C.: Department of Commerce, September 13, 2022), https://www.federalregister.gov/documents/2022/09/13/2022-19430/request-for-comments-concerning-the-imposition-of-section-1758-technology-export-controls-on;
Federal Register, *Request for Information; National Biotechnology and Biomanufacturing Initiative*, (Washington, D.C.: Office of Science and Technology Policy, December 20, 2022), https://www.federalregister.gov/documents/2022/12/20/2022-27600/request-for-information-national-biotechnology-and-biomanufacturing-initiative;
Federal Register, *Accelerating Innovations in Emerging Technologies*, (Washington, D.C.: Department of Energy, November 8, 2022), https://www.federalregister.gov/documents/2022/11/08/2022-24250/accelerating-innovations-in-emerging-technologies;
Federal Register, *Request for Comments on Artificial Intelligence Export Competitiveness*, (Washington, D.C.: Department of Commerce, August 16, 2022), https://www.federalregister.gov/documents/2022/08/16/2022-17576/request-for-comments-on-artificial-intelligence-export-competitiveness;
Federal Register, *Public Wireless Supply Chain Innovation Fund Implementation*, (Washington, D.C.: Department of Commerce, December 13, 2022), https://www.federalregister.gov/documents/2022/12/13/2022-26938/public-wireless-supply-chain-innovation-fund-implementation;
Federal Register, *Commerce Control List: Controls on Certain Marine Toxins*, (Washington, D.C.: Department of Commerce, May 23, 2022), https://www.federalregister.gov/documents/2022/05/23/2022-10907/commerce-control-list-controls-on-certain-marine-toxins.

[80] Rotolo, Hicks, and Martin, "What Is an Emerging Technology?" 8.

[81] Rotolo, Hicks, and Martin, "What Is an Emerging Technology?"

[82] Yoshizumi Ishino, Mart Krupovic, and Patrick Forterre, "History of CRISPR-Cas from Encounter with a Mysterious Repeated Sequence to Genome Editing Technology," *Journal of Bacteriology* 7, (April 1, 2018), https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5847661/.

[83] "Networks Course blog for INFO 2040/CS 2850/Econ 2040/SOC 2090: The History of PageRank and Iterative Searching Algorithms," Cornell University, October 25, 2017, https://blogs.cornell.edu/info2040/2017/10/25/the-history-of-pagerank-and-iterative-searching-algorithms/.